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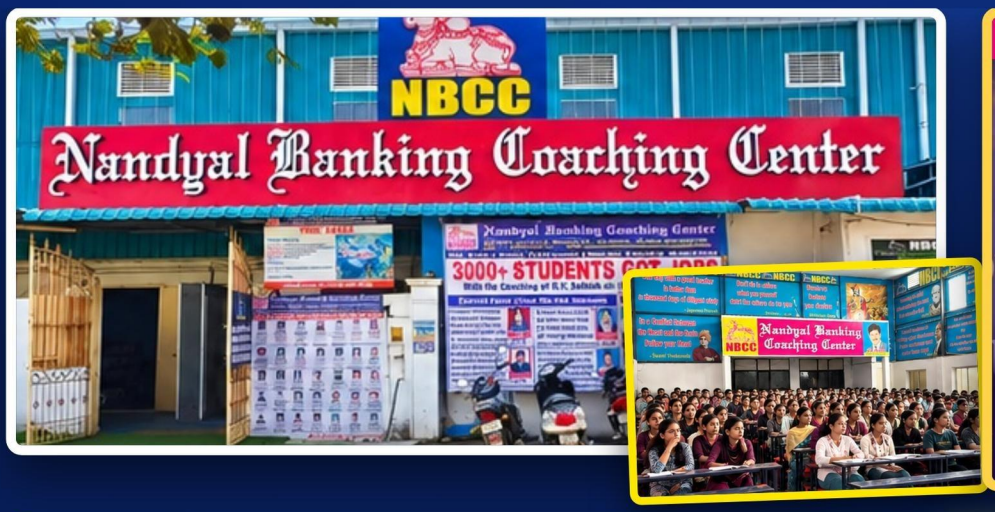



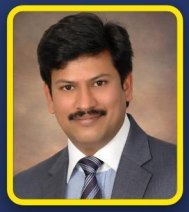

UNDER THE GUIDANCE OF

G. V. SATISH

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INTERVIEW PANEL MEMBER

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Prepared by

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About the Exam & How to Use This Book

Online examination – Assistant Manager (Engineering-Civil)

#	Test (not by sequence)	Questions	Marks	Time
1	**Professional / Subject Knowledge (this book)**	60	60	55 min
2	General Awareness	40	40	20 min
3	English Language	40	40	25 min
4	Reasoning & Computer Aptitude	30	30	25 min
5	Data Analysis & Interpretation and Quantitative Aptitude	30	30	25 min
6	Language & Comprehension Abilities – Descriptive	2	30	30 min
	Total	**202**	**230**	**3 hours**

- **Negative marking**: ¼ of the marks of the question for each wrong answer; no penalty for a blank.
- **Qualifying marks** in Professional Knowledge: **40%** (UR), **35%** (OBC/EWS/SC/ST/PwBD/ExSM). Same for the Descriptive test.
- Shortlisting for interview / DV up to **1:5**. Eligibility: **B.E./B.Tech (Civil)**; age 18–28 years (as on 15.11.2026). Pay scale **₹40,000–1,40,000 (E-1, IDA)**.
- Roughly **1 minute per question**: these notes are built for recall. Each section ends with a **Previously Asked / Likely Questions** box; stars show weightage (★★★ = must-do).

Priority order of subjects (by usual weightage)

#	Subject	Syllabus part
1	Strength of Materials, Engineering Mechanics & Structural Analysis	A (i–iii)
2	RCC Design & IS 456; Concrete Technology & Prestressed Concrete	A (v), H
3	Soil Mechanics, Foundation Engineering & Soil Improvement	B
4	Fluid Mechanics & Hydraulics	C (i–ii)
5	Environmental Engineering (Water, Waste Water, Air, MSW, Noise)	D
6	Transportation Engineering (Highways, Pavements, Traffic)	E
7	Surveying, GIS & GPS	F
8	Steel Structures & IS 800	A (vi)
9	Hydrology & Irrigation	C (iii–iv)
10	Engineering Materials & Building Construction	A (iv)
11	Project Management, Planning, Estimating & Contracts	G
12	Last-Day Revision (formula & value sheet)	All
13	500 Most Expected Questions & Answers	All

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1. Engineering Mechanics & Strength of Materials

> **NOTE**
>
> Mechanics and SOM together usually give **6–9 questions** in Civil AE/JE/PSU papers. Most are direct formula or ratio questions: Lami's theorem, MI of standard sections, m = 2j − 3, E–G–K relations, max BM/deflection coefficients (WL/4, $wL^2/8$, $5wL^4/384EI$), shear-stress ratios (1.5, 4/3), Euler effective lengths, Mohr's circle and the theories of failure. Learn the tables in this chapter by heart; there is very little derivation.

1.1 Forces, Resultant & Equilibrium ★★★

- **Force** is a **vector**. It is defined by magnitude, direction, sense and point of application. SI unit: **newton (N)** = kg·m/s². 1 kgf = **9.81 N**.
- **Scalar** quantities: mass, length, time, speed, work, energy, power. **Vector** quantities: force, displacement, velocity, acceleration, momentum, moment.
- **Principle of transmissibility**: a force can be moved anywhere along its **line of action** without changing its external effect on a **rigid body**. It does not hold for internal effects or deformable bodies.
- **Coplanar concurrent** forces: lines of action lie in one plane and meet at one point. **Coplanar non-concurrent** forces: in one plane but not through one point. **Collinear** forces: on the same line of action. **Like parallel** forces act in the same sense; **unlike parallel** forces act in opposite senses.
- **Resultant** = a single force with the same effect as the whole system. **Equilibrant** = equal to the resultant, opposite in sense and on the same line.
- **Parallelogram law**: if two forces acting at a point are shown by two adjacent sides of a parallelogram, the **diagonal through that point** gives the resultant.
- **Triangle law**: if two forces are drawn head to tail as two sides of a triangle, the **closing side, taken in the opposite order**, is the resultant. If three forces in equilibrium are drawn in order, they form a **closed triangle**.
- **Polygon law**: for more than two concurrent forces, the closing side of the force polygon is the resultant. A **closed polygon** means equilibrium (for concurrent forces).
- **Lami's theorem**: if **three coplanar concurrent forces** are in equilibrium, each force is proportional to the **sine of the angle between the other two**: P/sin α = Q/sin β = R/sin γ. It applies **only to three forces**, and all three must act away from or all towards the point.
- **Varignon's theorem (principle of moments)**: the moment of the resultant about any point = the **algebraic sum of the moments of the components** about the same point. It is used to locate the resultant and to find centroids.
- **Moment** = force × perpendicular distance. Unit: **N·m**. Clockwise and anticlockwise moments are given opposite signs.
- **Couple** = two **equal, parallel, unlike** forces that are not collinear. Moment of couple = F × arm. The **resultant force of a couple is zero**. Its moment is the **same about every point** in the plane (a **free vector**). A couple **cannot be balanced by a single force**, only by an equal and opposite couple.
- A force acting at a point can be replaced by an **equal force at another point plus a couple** (force–couple system).
- **Free body diagram (FBD)**: the body is isolated and **all external forces and reactions** are drawn on it. Internal forces are not shown.
- **Two-force member**: equilibrium only when the two forces are **equal, opposite and collinear**. **Three-force member**: the three forces must be **concurrent or parallel**.
- Support reactions: **roller** gives 1 reaction (normal to the surface); **hinge/pin** gives 2 (H, V); **fixed** gives 3 (H, V, M).

> **KEY FORMULAE**
>
> - Resultant of P and Q at angle θ: $R = \sqrt{(P^2 + Q^2 + 2PQ\cos\theta)}$; $\tan\alpha = Q\sin\theta / (P + Q\cos\theta)$, where α is measured from P.
> - θ = 0 → R = P + Q (maximum); θ = 180° → R = P − Q (minimum); θ = 90° → $R = \sqrt{(P^2 + Q^2)}$.
> - Two equal forces P at angle θ: R = **2P cos(θ/2)**. At θ = 120°, R = P.
> - Resolution: $\Sigma H = \Sigma F\cos\theta$, $\Sigma V = \Sigma F\sin\theta$, $R = \sqrt{(\Sigma H^2 + \Sigma V^2)}$, $\tan\alpha = \Sigma V/\Sigma H$.
> - Lami: P/sin α = Q/sin β = R/sin γ.

Force system	Conditions of equilibrium	No. of equations
Collinear	ΣF = 0	**1**
Coplanar concurrent	ΣH = 0, ΣV = 0	**2**
Coplanar parallel	ΣF = 0, ΣM = 0	**2**
Coplanar non-concurrent (general)	ΣH = 0, ΣV = 0, ΣM = 0	**3**
Space concurrent	$\Sigma F_x = \Sigma F_y = \Sigma F_z = 0$	**3**
Space general	3 force + 3 moment equations	**6**

> **MEMORY TRICK**
>
> In Lami's theorem each force is paired with the angle **opposite** it, the angle it is not part of. Think "sine of the gap between the other two".

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- Lami's theorem applies to how many forces? → **Three coplanar concurrent forces in equilibrium**.
- Two equal forces P act at 120°. Resultant? → **P**.
- Resultant force of a couple? → **Zero**. Its moment is the same about every point.
- The principle of moments is also called → **Varignon's theorem**.
- Number of equilibrium equations for a general coplanar system → **3**.
- A couple can be balanced by → **an equal and opposite couple only**.

1.2 Friction, Centroid & Moment of Inertia ★★★

Friction

- **Limiting friction** = the maximum friction just before motion starts. **Coefficient of friction** μ = F/N.
- **Laws of static (dry/Coulomb) friction**: friction acts **opposite to the tendency of motion**. Limiting friction is ∝ **normal reaction** and is **independent of the area of contact**. It depends on the **nature of the surfaces**.
- **Laws of kinetic friction**: kinetic friction is **less than limiting friction**. It is practically **independent of velocity** at moderate speeds. The ratio F_k/N stays constant.
- Order: **static (limiting) > kinetic (sliding) > rolling** friction.
- **Angle of friction** φ is the angle between the resultant reaction and the normal: **tan φ = μ**.
- **Angle of repose** α is the maximum slope at which a body rests on an inclined plane without sliding. **Angle of repose = angle of friction**, so tan α = μ.
- **Cone of friction**: the cone with semi-vertex angle φ, generated by the limiting resultant reaction.
- **Ladder problems**: take μ at the floor and at the wall. If the wall is smooth, the wall reaction is horizontal (normal to the wall). Use ΣH = 0, ΣV = 0 and ΣM = 0 about the foot.
- **Wedge**: a small device for lifting heavy loads or adjusting position. Draw an FBD for the wedge and one for the block. Friction acts on all contact faces. A wedge is **self-locking** if it stays in place after the force is removed, which needs wedge angle ≤ 2φ (for friction on both faces).
- **Belt friction**: $T_1/T_2 = e^{\mu\theta}$, with θ in radians.

KEY FORMULAE

- Body on an inclined plane of angle α: it is on the point of sliding when **tan α = μ**.
- Least force to drag a body on a horizontal plane: P_{min} = **W sin φ**, applied at angle φ to the horizontal.
- Least force on an inclined plane (up the plane): P_{min} = W sin(α + φ), acting at φ to the plane.

Centroid & Centre of Gravity

- **Centroid** is the geometric centre of an area, line or volume. **Centre of gravity** is the point through which the weight acts. For a homogeneous body they coincide.
- $\bar{x} = \Sigma A\,x / \Sigma A$. For a cut-out (hole), use **negative area**.
- If a figure has an axis of symmetry, the centroid lies **on that axis**.

Shape	Centroid position
Rectangle	b/2, d/2
Triangle	**h/3 from base** (2h/3 from apex); intersection of medians
Semicircle (area)	**4r/(3π) ≈ 0.424r** from the diameter
Quarter circle (area)	4r/(3π) from each straight edge
Semicircular arc (wire)	**2r/π** from the diameter
Trapezium (parallel sides a bottom, b top)	$\bar{y} = (h/3)(2b + a)/(a + b)$ from side a
Solid hemisphere	**3r/8** from the flat face
Hollow hemisphere (thin shell)	**r/2** from the flat face
Solid right circular cone	**h/4 from base**
Hollow cone (surface only)	**h/3 from base**
Parabolic spandrel ($y = kx^2$, area under curve)	3a/4 from vertex along x; 3h/10 from base

Moment of Inertia (second moment of area)

- $I = \int y^2\,dA$. Unit: **mm^4 or m^4**. It is always **positive**. It is the minimum about the **centroidal axis**.
- **Parallel axis theorem**: $I_{AB} = I_G + A\,h^2$, where h is the distance between the parallel axes. It works only from a centroidal axis.
- **Perpendicular axis theorem** (plane laminae only): $\mathbf{I_z = I_x + I_y}$. This gives the polar MI J.
- **Radius of gyration**: $k = \sqrt{(I/A)}$. For a rectangle about its centroidal axis, $k = d/\sqrt{12}$. For a circle, **k = d/4**.
- **Section modulus** $Z = I/y_{max}$ (mm^3). It measures **bending strength**. **Polar modulus** $Z_p = J/R$ measures torsional strength.
- **Product of inertia** $I_{xy} = \int xy\,dA$. It can be +, − or zero. It is **zero if either axis is an axis of symmetry**. Axes with $I_{xy} = 0$ are the **principal axes**.
- **Mass MI** ($kg·m^2$) is used in dynamics. Examples: solid sphere $2MR^2/5$; disc $MR^2/2$; thin rod about its centre $ML^2/12$, about one end $ML^2/3$; ring MR^2.

Section	I about centroidal axis	I about base / other	Z (bending)
Rectangle b × d	**$bd^3/12$**	About base: **$bd^3/3$**	**$bd^2/6$**

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Square side a	$a^4/12$ (same about any centroidal axis, including the diagonal)	About base: $a^4/3$	$a^3/6$; about diagonal: $\mathbf{a^3/(6\sqrt{2}) \approx 0.118a^3}$
Triangle b × h	$\mathbf{bh^3/36}$	About base: $\mathbf{bh^3/12}$; about apex (parallel to base): $\mathbf{bh^3/4}$	Top fibre $bh^2/24$; bottom $bh^2/12$
Circle dia d	$\mathbf{\pi d^4/64}$	Polar J = $\mathbf{\pi d^4/32}$	$\mathbf{\pi d^3/32}$
Hollow circle D, d	$\pi(D^4 - d^4)/64$	$J = \pi(D^4 - d^4)/32$	$\pi(D^4 - d^4)/(32D)$
Semicircle radius r	≈ $\mathbf{0.11\ r^4}$ (= $0.1098\ r^4$) about the centroidal axis parallel to the diameter	About diameter: $\mathbf{\pi r^4/8 = \pi d^4/128}$	–
Quarter circle radius r	≈ $0.055\ r^4$	About a straight edge: $\mathbf{\pi r^4/16}$	–
Thin ring (mean radius R, thickness t)	$\pi R^3 t$	$J = 2\pi R^3 t$	–

MEMORY TRICK

Rectangle "**12–3**": divide by 12 at the centre, by 3 at the base. Triangle "**36–12–4**": centroid, base, apex. Circle "**64–32**": I = $\pi d^4/64$ and J = $\pi d^4/32$. Z of a circle is also $\pi d^3/32$. Twice that, $\pi d^3/16$, is the polar modulus.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Angle of repose is equal to → **angle of friction** ($\tan = \mu$).
- Does limiting friction depend on the area of contact? → **No**.
- MI of a triangle about its base → $\mathbf{bh^3/12}$.
- Centroid of a solid hemisphere from its flat face → **3r/8**.
- Radius of gyration of a circular section of diameter d → **d/4**.
- The perpendicular axis theorem applies to → **plane laminae (areas) only**.

1.3 Trusses, Kinematics & Kinetics ★★☆

Trusses (pin-jointed plane frames)

- Assumptions: joints are **frictionless pins**, loads act **only at the joints**, and member self-weight is neglected. So every member is a **two-force member** carrying **axial force only**.
- **Perfect frame**: **m = 2j − 3** (m = members, j = joints). It is stable and statically determinate. **Deficient frame**: m < 2j − 3, so it is unstable (a mechanism). **Redundant frame**: m > 2j − 3, so it is statically indeterminate.
- For a space truss: m = **3j − 6**.
- **Method of joints**: use equilibrium at each joint ($\Sigma H = 0$, $\Sigma V = 0$). Start at a joint with **no more than 2 unknowns**. It finds all member forces.
- **Method of sections (Ritter's method)**: cut through **no more than 3 members** whose forces are unknown, then take moments. It is quickest for forces in a few chosen members.
- **Graphical method**: Maxwell diagram (force polygon), using Bow's notation.
- **Zero-force member rules**: (i) at an unloaded joint with two non-collinear members, **both are zero**. (ii) At an unloaded joint with three members, two of them collinear, the **third (non-collinear) member is zero**.
- Tension members are called **ties**. Compression members are called **struts**.

Kinematics

- Uniform acceleration: $v = u + at$; $s = ut + \frac{1}{2}at^2$; $v^2 = u^2 + 2as$; distance in the nth second $s_n = u + a(2n - 1)/2$.
- Free fall: $a = g = 9.81\ m/s^2$. Time to reach maximum height = u/g. Maximum height = $u^2/(2g)$.
- **Projectile** (launched at u, θ from the horizontal; air resistance neglected): the horizontal velocity stays **constant**. The path is a **parabola**.
- Range is the **same for θ and (90° − θ)**, i.e. complementary angles. Maximum range is at **θ = 45°**, where $R_{max} = u^2/g$ and $H = R_{max}/4$.
- At the highest point, velocity = u cos θ (horizontal only) and acceleration = g (downward).
- Projectile on a plane inclined at α (fired up the plane): maximum range = $u^2/[g(1 + \sin\alpha)]$ when the projection angle with the horizontal is **45° + α/2**.
- Angular motion: $\omega = \omega_0 + \alpha t$; $v = r\omega$; centripetal acceleration = $v^2/r = r\omega^2$; 1 rev = 2π rad; $\omega = 2\pi N/60$.

KEY FORMULAE – PROJECTILE

- Time of flight T = $\mathbf{2u \sin\theta / g}$
- Maximum height H = $\mathbf{u^2 \sin^2\theta / (2g)}$
- Horizontal range R = $\mathbf{u^2 \sin 2\theta / g}$
- Equation of path: $y = x \tan\theta - g x^2 / (2u^2 \cos^2\theta)$
- H/R = tan θ / 4. When R = H, tan θ = 4 (θ ≈ 76°).

Kinetics

- **Newton's 1st law** defines inertia (and force qualitatively). The **2nd law** gives F = ma = rate of change of momentum. The **3rd law** says action and reaction are equal and opposite and act on **different bodies**.
- **D'Alembert's principle**: adding the inertia force (−ma) turns a dynamic problem into a static one: F − ma = 0 (dynamic equilibrium).
- Lift problems: moving up with acceleration a, R = m(g + a). Moving down, R = m(g − a). In free fall, R = 0 (weightlessness).

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- **Work** = F·s cos θ (J). **Power** = work/time (W); 1 hp (metric) = **735.5 W**; 1 hp (British) = 746 W. **KE** = ½mv². **PE** = mgh.
- **Work–energy principle**: work done by all forces = **change in KE**.
- **Impulse** = F·t = **change in momentum** (N·s). **Law of conservation of momentum**: with no external force, total momentum is constant. Example: gun recoil, M V = m v.
- **Coefficient of restitution** e = (relative velocity of separation)/(relative velocity of approach) = $(v_2 - v_1)/(u_1 - u_2)$.
- **e = 1**: perfectly elastic collision, KE conserved. **e = 0**: perfectly plastic (inelastic), bodies move together and KE loss is maximum. 0 < e < 1: real bodies. **Momentum is conserved in all collisions**.
- Equal masses in an elastic head-on impact **exchange velocities**.
- Ball dropped from height h rebounds to **e^2h**. So e = $\sqrt{(h_2/h_1)}$.

Simple Machines

- **Mechanical advantage** MA = W/P (load/effort). **Velocity ratio** VR = distance moved by effort / distance moved by load. **Efficiency** η = MA/VR.
- Ideal machine: η = 100%, so MA = VR. In practice **MA < VR**. VR depends only on geometry and **does not change with friction**.
- **Law of machine**: P = mW + C, where C = effort lost in friction. **Maximum MA = 1/m. Maximum η = 1/(m × VR)**.
- **Reversible machine**: η **> 50%**. The load can drive the machine backwards when the effort is removed. **Irreversible (self-locking)**: η **≤ 50%**. Screw jacks are kept self-locking for safety.

Machine	Velocity ratio
Simple wheel & axle	D/d
Differential wheel & axle	$2D/(d_1 - d_2)$
Weston differential pulley block	2D/(D − d)
Simple screw jack	**2πL / p** (L = handle length, p = pitch)
Differential screw jack	$2\pi L/(p_1 - p_2)$
Worm & worm wheel	L × T / r (T = teeth on wheel, single-start worm)
Pulley system – 1st order (n movable pulleys)	2^n
Pulley system – 2nd order (n pulleys in all)	**n**
Pulley system – 3rd order	$2^n - 1$
Simple gear drive	T_{driven}/T_{driver}

- Screw jack: the maximum efficiency is **(1 − sin φ)/(1 + sin φ)**. It occurs at helix angle α = 45° − φ/2.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- A truss has 9 joints. Members needed for a perfect frame? → **15** (2×9 − 3).
- Angle of projection for maximum horizontal range → **45°**.
- Coefficient of restitution for a perfectly plastic body → **0**.
- Condition for a reversible machine → **η > 50%**.
- Impulse is equal to → **change of momentum**.
- Maximum number of unknown members that can be cut in the method of sections → 3.

1.4 Simple Stresses, Strains & Elastic Constants ★★★

- **Stress** = internal resisting force per unit area, σ = P/A. Units: N/mm² = **MPa**. **Strain** = δL/L and is dimensionless.
- **Hooke's law**: within the **limit of proportionality**, stress ∝ strain. σ = Eε.
- **Young's modulus E** = σ/ε (direct). **Modulus of rigidity G (C or N)** = τ/φ (shear). **Bulk modulus K** = direct stress / volumetric strain (σ/ε_v). Their units are the same as stress.
- **Poisson's ratio ν (1/m)** = lateral strain / longitudinal strain. Lateral strain has the **opposite sign**.
- Theoretical range: **−1 < ν ≤ 0.5**. For engineering materials, **0 to 0.5**. ν = 0.5 means an **incompressible material** (no volume change, K → ∞).
- Number of independent elastic constants: **2** for an isotropic, homogeneous material; **9** for orthotropic; **21** for anisotropic.
- **Isotropic**: same properties in all directions. **Homogeneous**: same properties at every point. **Ductile** materials show large plastic deformation (mild steel, copper, aluminium). **Brittle** materials fail with little deformation (cast iron, concrete, glass). **Malleability**: can be beaten into sheets. **Toughness**: energy absorbed up to fracture. **Resilience**: energy absorbed within the elastic limit.
- **Creep**: strain increasing with time under constant load. **Relaxation**: stress falling with time under constant strain. **Fatigue**: failure under repeated or cyclic stress below the ultimate stress. **Endurance limit**: the stress below which failure does not occur for infinite cycles (for steel, about **10^6–10^7 cycles**).
- **Factor of safety** = ultimate (or yield) stress / working stress.

Point on mild-steel stress–strain curve (tension, in order)	Key fact
1. Limit of proportionality	End of the straight line; Hooke's law holds up to here
2. Elastic limit	Just above the proportional limit; no permanent set when unloaded
3. Upper yield point	Stress drops suddenly; depends on the cross-section and testing speed

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4. Lower yield point	Taken as the **yield stress** ($f_y \approx 250$ N/mm² for E250 steel, IS 2062)
5. Strain hardening	Stress rises again after the yield plateau
6. Ultimate stress	**Maximum engineering stress**; **necking** starts here
7. Breaking / fracture point	Engineering stress is lower than ultimate, but **true stress is highest**

- Materials with no clear yield point (HYSD bars, aluminium, high-tensile steel) use **0.2% proof stress** (offset method).
- Mild steel fails in tension with a **cup-and-cone fracture**, caused by shear at 45°. Cast iron in tension fails on a **flat plane** normal to the axis. Cast iron in compression fails on a plane at about 45°–55°.
- Ductile material in torsion fails on a plane **⊥ to the axis** (maximum shear). Brittle material in torsion fails on a **45° helix** (maximum tension).

Material	E (N/mm²)	Poisson's ratio v
Steel	**2×10^5** (IS 456 / IS 800)	0.25–0.33; **0.3** (IS 800)
Cast iron	$\approx 1 \times 10^5$ ($0.8–1.5 \times 10^5$)	0.23–0.27
Aluminium	$\approx 0.7 \times 10^5$	≈ 0.33
Copper	$\approx 1.0–1.2 \times 10^5$	≈ 0.34
Concrete	$E_c = 5000\sqrt{f_{ck}}$ (IS 456)	0.1–0.2; **0.2** for design
Rubber	very low	≈ **0.5**
Cork	–	≈ **0** (used as bottle stopper)
Timber	$\approx 0.1 \times 10^5$	–

- G for steel ≈ **0.77×10^5 N/mm²** (IS 800: 0.769×10^5). Since G = E/2(1 + v), G lies between **E/3 and E/2**.
- Coefficient of thermal expansion: steel ≈ **12×10^{-6} /°C**; concrete ≈ $10–12 \times 10^{-6}$ /°C. These are almost equal, which is why RCC works.

KEY FORMULAE – ELASTIC CONSTANTS

- **E = 2G(1 + v)**
- **E = 3K(1 − 2v)**
- **E = 9KG / (3K + G)**
- v = (3K − 2G) / (6K + 2G)
- v = 0.5 → E = 3G and K = ∞; v = 0.25 → E = 2.5G; v = 0 → E = 2G = 3K.
- Volumetric strain of a bar under axial σ: $\varepsilon_v = \varepsilon(1 - 2v)$
- Cube under equal stresses σ on all three axes: $\varepsilon_v = 3\sigma(1 - 2v)/E$
- Rectangular block: $\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z$. For a cylinder: $\varepsilon_v = \varepsilon_L + 2\varepsilon_D$. For a sphere: $\varepsilon_v = 3\varepsilon_D$.
- Diagonal strain of a square block in pure shear = φ/2. So pure shear τ gives tension and compression of magnitude τ on the 45° planes.

KEY FORMULAE – ELONGATION

- Prismatic bar: δ = **PL / AE**. Stepped bar: $\delta = (P/E) \Sigma L_i/A_i$.
- Tapering circular bar (d_1 to d_2): δ = **$4PL / (\pi E d_1 d_2)$**
- Tapering rectangular bar (width b_1 to b_2, thickness t): $\delta = PL \ln(b_1/b_2) / [E t (b_1 - b_2)]$
- Prismatic bar under self-weight: **$\delta = \gamma L^2 / (2E) = WL / (2AE)$**. This is **half** the elongation from the same load applied at the end.
- Conical bar under self-weight: **$\delta = \gamma L^2 / (6E)$**.
- Bar of uniform strength (self-weight): $A = A_1 e^{\gamma x/\sigma}$.
- Thermal stress (fully restrained): **$\sigma = E \alpha \Delta T$**. It is **independent of the length and area**. If the support yields by Δ: $\sigma = E(\alpha \Delta T L - \Delta)/L$.
- Composite bar (two materials sharing a load): equal strain, so $\sigma_1/E_1 = \sigma_2/E_2$ and $P = \sigma_1 A_1 + \sigma_2 A_2$. Modular ratio $m = E_s/E_c$.
- Composite bar heated (steel with copper): the material with the **higher α (copper)** goes into **compression**; steel goes into tension. $\sigma_s A_s = \sigma_c A_c$.

Strain Energy & Impact

- **Strain energy** $U = \frac{1}{2} P \delta = \sigma^2 V / (2E)$. **Proof resilience** = maximum strain energy stored up to the elastic limit. **Modulus of resilience** = proof resilience per unit volume = $\sigma_e^2/(2E)$. **Modulus of toughness** = area under the whole stress–strain curve.
- Shear strain energy = $\tau^2 V / (2G)$. Torsion (solid shaft): $U = (\tau^2/4G) \times V$. Hollow shaft: $(\tau^2/4G)(D^2 + d^2)/D^2 \times V$.

Type of loading	Stress produced
Gradual load P	σ = P/A
Sudden load P (h = 0)	σ = **2P/A** (twice the gradual value)
Impact (falling from height h)	$\sigma = (P/A)[1 + \sqrt{(1 + 2AEh/(PL))}]$
Impact, h large compared with δ	$\sigma \approx \sqrt{(2EPh/(AL))}$

MEMORY TRICK

"**2G, 3K**": E = 2G(1 + v) = 3K(1 − 2v). Shear goes with **+** and 2; bulk goes with **−** and 3. Self-weight elongation is **½** for a prism and **⅙** for a cone ($\gamma L^2/2E$ and $\gamma L^2/6E$).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- E = 2.5G. Poisson's ratio? → **0.25**.
- Maximum value of Poisson's ratio → **0.5**.
- Stress due to a suddenly applied load compared with a gradual one → **Twice**.
- Thermal stress in a restrained bar depends on → **E, α, ΔT; not on length or area**.
- Elongation of a bar under its own weight → **WL/2AE**.
- Independent elastic constants for an isotropic material → **2**.

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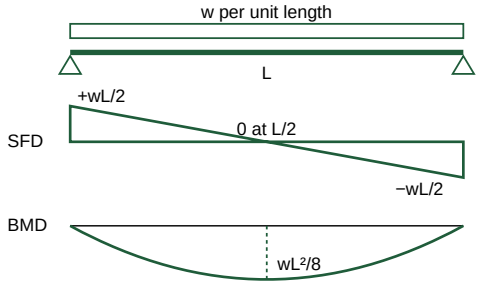
1.5 Shear Force & Bending Moment ★★★

- **Shear force (SF)** at a section = algebraic sum of all vertical forces on **one side** of the section. **Bending moment (BM)** = algebraic sum of the moments of those forces about the section.
- **Sign convention** (usual): SF is **positive** when the left part tends to move **up** relative to the right ("left up, right down"). BM is **positive (sagging)** when the beam bends concave upward. **Hogging** (concave down) is negative; it occurs at cantilever supports and over continuous supports.
- **Relationships**: **dM/dx = V** (slope of the BMD = SF), and **dV/dx = −w** (slope of the SFD = load intensity, downward load taken as negative).
- The BM is **maximum where the SF is zero** (or changes sign).
- Change in BM between two sections = **area of the SFD** between them. Change in SF = area of the load diagram.
- **Point load → sudden jump** in the SFD and a **kink** in the BMD. **Concentrated couple** → no change in SF, but a **sudden jump in BM** equal to the couple.
- **Point of contraflexure (inflexion)**: where the BM **changes sign** (BM = 0 inside the span). It occurs in **overhanging, fixed, propped and continuous** beams. It never occurs in a simply supported beam or cantilever under gravity loads.
- **Point of inflexion** is strictly the point where the curvature of the elastic curve changes sign. It coincides with the point of contraflexure.
- Beam of total length L with equal overhangs a on both sides and UDL over the whole length: **zero BM at the centre** when a = **L/4**. The **least maximum BM** (hogging at supports = sagging at centre) occurs when a = **0.207 L**.

Load on beam	SFD shape	BMD shape
No load (between point loads)	Constant (horizontal)	Linear (1st degree)
UDL	Linear (inclined)	**Parabolic (2nd degree)**
UVL (triangular)	**Parabolic (2nd degree)**	**Cubic (3rd degree)**
Parabolic load	Cubic	4th degree
Couple only	Constant / zero	Constant (rectangle), with a jump at the couple

Beam & load (span L)	Max SF	Max BM	Position of max BM
Cantilever, point W at free end	**W**	**WL**	Fixed end
Cantilever, UDL w/m over full span	**wL**	**$wL^2/2$**	Fixed end
Cantilever, UVL 0 at free end to w at fixed end	wL/2	**$wL^2/6$**	Fixed end
Cantilever, UVL w at free end to 0 at fixed end	wL/2	**$wL^2/3$**	Fixed end
Cantilever, couple M at free end	0	M (constant)	Throughout
SS, central point W	**W/2**	**WL/4**	Centre
SS, point W at distances a and b from the supports	Wb/L (larger reaction)	**Wab/L**	Under the load
SS, UDL w over full span	**wL/2**	**$wL^2/8$**	Centre
SS, UVL 0 at one end to w at other end	wL/3 (at the heavier end)	**$wL^2/(9\sqrt{3}) \approx 0.064wL^2$**	**$L/\sqrt{3} = 0.577L$** from the zero end
SS, triangular load peak w at centre	wL/4	**$wL^2/12$**	Centre
SS, couple M at centre	M/L	M/2 (on each side of the couple)	At the couple
SS, two equal loads W at the third points	W	WL/3 (constant middle third; pure bending)	Middle third

- Reactions for an SS beam with UVL (0 to w): **wL/6** at the zero end and **wL/3** at the heavier end. Total load = wL/2.
- SS beam with a UDL: the BMD is a parabola with maximum **$wL^2/8$**. The SFD is linear from +wL/2 to −wL/2 and crosses zero at mid-span.



Simply supported beam with full-span UDL: linear SFD, parabolic BMD (maximum $wL^2/8$ at mid-span, where SF = 0).

MEMORY TRICK

"**Load → Shear → Moment**": each step goes **one degree higher** (integration). Zero load gives constant SF and linear BM. UDL gives linear SF and parabolic BM. UVL gives parabolic SF and cubic BM. Max BM **"4–8–2"**: SS point WL/4, SS UDL $wL^2/8$, cantilever UDL $wL^2/2$.

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- BMD shape for a UDL → **Parabola (2nd degree)**.
- BM is maximum where the SF is → **Zero (changes sign)**.
- Points of contraflexure occur in → **overhanging / fixed / continuous beams**.
- Maximum BM in an SS beam with UVL zero at one end → **$wL^2/(9\sqrt{3})$**, at **$L/\sqrt{3}$** from the zero end.
- A concentrated couple causes in the BMD → **a sudden jump** (no change in the SFD).
- Maximum BM of a cantilever with UDL → **$wL^2/2$**.

1.6 Bending & Shear Stresses in Beams ★★★

- **Assumptions of simple bending (Euler–Bernoulli)**: the material is homogeneous and isotropic and obeys Hooke's law. **Plane sections remain plane**. E is the same in tension and compression. The radius of curvature is large compared with the depth. The beam is initially straight. The load acts in the plane of symmetry.
- **Pure bending** = constant BM with zero SF. Example: the middle third of an SS beam with two equal loads at the third points.
- **Neutral axis (NA)**: the layer with zero stress and zero strain. It passes through the **centroid** of the section (for elastic bending). Bending stress varies **linearly** with distance from the NA and is maximum at the extreme fibres.
- **Neutral layer/surface**: the layer that is neither stretched nor compressed. The NA is where the neutral layer meets the cross-section.
- **Moment of resistance** M = σ Z. For equal allowable stress, a section with the larger Z is stronger.
- The **strongest rectangular beam that can be cut from a circular log** of diameter D has **$d/b = \sqrt{2}$** ($b = D/\sqrt{3}$, $d = \sqrt{(2/3)}\,D$). The **stiffest** beam has **$d/b = \sqrt{3}$**.
- For the same area, an I-section is better than a rectangle, which is better than a square, which is better than a circle (Z per area). A square with its **side horizontal** is stronger than a square with its diagonal vertical. The ratio is **$\sqrt{2}$** ($Z = a^3/6$ against $a^3/(6\sqrt{2})$).
- **Beam of uniform strength**: the maximum bending stress σ is the same at every section. This is achieved by (i) constant depth with varying width ($b \propto M$), (ii) constant width with varying depth ($d \propto \sqrt{M}$), or (iii) varying both. Examples: leaf springs and tapered girders.
- **Flitched (composite) beam**: timber strengthened with steel plates. The strain at a common fibre is equal, so **$\sigma_s = m\,\sigma_w$** at the same distance from the NA ($m = E_s/E_w$, typically ≈ 20). Use the **equivalent (transformed) section** by multiplying the steel width by m. Total $M = M_{timber} + M_{steel}$.
- **Shape factor** = plastic modulus Z_p / elastic modulus Z_e = M_p/M_y. Values: rectangle **1.5**, solid circle **1.70 (16/3π)**, I-section ≈ **1.12–1.14**, diamond **2.0**, triangle **2.34**, thin hollow circle ≈ 1.27.

KEY FORMULAE

- Flexure formula: **$M/I = \sigma/y = E/R$**
- $\sigma_{max} = M/Z$. Rectangle: $\sigma = 6M/(bd^2)$. Solid circle: $\sigma = 32M/(\pi d^3)$.
- Shear stress at a layer: **$\tau = V\,A\,\bar{y}\,/\,(I\,b)$**, where $A\bar{y}$ = first moment of the area above the layer about the NA and b = width at that layer.
- Rectangle: $\tau = (V/2I)(d^2/4 - y^2)$. The distribution is **parabolic**, with $\tau_{max} = 1.5\,V/(bd)$ at the NA.
- Circle: $\tau_{max} = (4/3)\,\tau_{avg}$ at the NA.

Section	τ_{max} / τ_{avg}	Where τ_{max} occurs
Rectangle / square (side horizontal)	**1.5 (3/2)**	Neutral axis
Solid circle	**4/3 ≈ 1.33**	Neutral axis
Thin-walled circular tube	**2.0**	Neutral axis
Triangle (base horizontal)	**1.5** (at NA: 4/3)	**Mid-height (h/2 from apex)**, not the NA
Diamond / square with diagonal vertical	**9/8 = 1.125**	d/8 above and below the NA
I-section	–	NA in the web. The **web carries about 90–95% of the shear**; there is a sudden jump in τ at the web–flange junction.

- Shear stress is **zero at the extreme fibres**. Bending stress is **zero at the NA**. So the two maxima occur at different points.
- In an I-section, the **flanges resist most of the bending** and the **web resists most of the shear**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Ratio of maximum to average shear stress for a rectangular section → **1.5**.
- Same ratio for a circular section → **4/3**.
- Strongest rectangular beam from a log: d/b → **$\sqrt{2}$**.
- Section modulus of a circle of diameter d → **$\pi d^3/32$**.
- Shape factor of a rectangular section → **1.5**.
- In a triangular section, maximum shear stress occurs at → **half the height**.

1.7 Deflection of Beams ★★★

- Differential equation of the elastic curve: **$EI\,d^2y/dx^2 = M$**. Then $EI\,d^3y/dx^3 = V$ and $EI\,d^4y/dx^4 = -w$.
- **EI = flexural rigidity**. Deflection ∝ 1/EI.

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- **Double integration method**: integrate M twice. Constants come from the boundary conditions (y = 0 at supports; dy/dx = 0 at a fixed end).
- **Macaulay's method**: a single BM expression with brackets <x − a>, valid for the whole beam. Useful for **several point loads**. Brackets are integrated as a whole and ignored when negative.
- **Moment-area method (Mohr's theorems)**. Theorem I: change in slope between two points = **area of the M/EI diagram** between them. Theorem II: deflection of B from the tangent at A = **moment of the M/EI area** about B. It is best for **cantilevers and symmetric SS beams**.
- **Conjugate beam method**: load the conjugate beam with M/EI. Then **slope = SF** and **deflection = BM** of the conjugate beam.
- **Strain energy / Castigliano's theorem**: $\delta = \partial U/\partial P$. **Unit load method** (virtual work): $\delta = \int M\, m\, dx / EI$. **Maxwell's reciprocal theorem**: $\delta_{ab} = \delta_{ba}$.

Real beam support	Conjugate beam support
Fixed end	**Free end**
Free end	**Fixed end**
Simple (hinge/roller) end support	Simple end support
Interior support	**Interior hinge**
Interior hinge	**Interior support**

Beam & load (span L)	Maximum slope θ	Maximum deflection δ
Cantilever, W at free end	**$WL^2/2EI$**	**$WL^3/3EI$**
Cantilever, UDL w full span	**$wL^3/6EI$**	**$wL^4/8EI$**
Cantilever, UVL 0 at free end to w at fixed end	$wL^3/24EI$	**$wL^4/30EI$**
Cantilever, moment M at free end	**ML/EI**	**$ML^2/2EI$**
Cantilever, W at distance a from the fixed end	$Wa^2/2EI$	Under the load: $Wa^3/3EI$; at the free end: $Wa^3/3EI + (Wa^2/2EI)(L - a)$
SS, central W	**$WL^2/16EI$**	**$WL^3/48EI$**
SS, UDL w full span	**$wL^3/24EI$**	**$5wL^4/384EI$**
SS, UVL 0 to w	–	≈ 0.00652 wL^4/EI (at 0.519L from the zero end)
SS, moment M at one end	ML/3EI (at that end), ML/6EI (other end)	$ML^2/(9\sqrt{3}\,EI) \approx 0.0642\, ML^2/EI$
Fixed–fixed, central W	0 at the ends	**$WL^3/192EI$**
Fixed–fixed, UDL w	0 at the ends	**$wL^4/384EI$**

Indeterminate beam	Key result
Fixed beam, UDL	End moment **$wL^2/12$** (hogging); mid-span **$wL^2/24$** (sagging); points of contraflexure at **0.211L** from each end
Fixed beam, central W	End moment **WL/8**; mid-span WL/8; contraflexure at **L/4** from each end
Fixed beam, eccentric W (a, b)	$M_A = Wab^2/L^2$, $M_B = Wa^2b/L^2$
Propped cantilever, UDL	Prop reaction **3wL/8**; fixed-end moment **$wL^2/8$**; maximum sagging $9wL^2/128$ at 3L/8 from the prop
Propped cantilever, central W	Prop reaction **5W/16**; fixed-end moment **3WL/16**
Two-span continuous beam (equal spans), UDL	Central support moment **$wL^2/8$**; central reaction 5wL/4

- Ratio of central deflections, SS beam : fixed beam. Under a central load: 1/48 : 1/192 = **4 : 1**. Under a UDL: 5/384 : 1/384 = **5 : 1**.
- Deflection of a cantilever with UDL ($wL^4/8EI$) is **9.6 times** that of an SS beam of the same span and load ($5wL^4/384EI$).
- Doubling the span multiplies the deflection by **8** under a point load (L^3) and by **16** under a UDL (L^4).

MEMORY TRICK

Cantilever "**2-3, 6-8**": point load θ = $WL^2/2EI$, δ = $WL^3/3EI$; UDL θ = $wL^3/6EI$, δ = $wL^4/8EI$. SS "**16-48, 24-384**". Fixed beam: **192** (point load) and **384** (UDL, without the 5).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Maximum deflection of an SS beam with central point load → **$WL^3/48EI$**.
- Maximum deflection of a cantilever with UDL → **$wL^4/8EI$**.
- Fixed end in the real beam becomes, in the conjugate beam → **Free end**.
- Reaction at the prop of a propped cantilever with UDL → **3wL/8**.
- Macaulay's method is useful for → **beams with several point loads (discontinuous loading)**.
- Fixing moment at the ends of a fixed beam with UDL → **$wL^2/12$**.

1.8 Torsion, Columns & Struts ★★★

Torsion of Circular Shafts

- Assumptions: the material is homogeneous and obeys Hooke's law. **Plane sections remain plane** and radii stay straight. The twist is uniform along the length.
- Shear stress varies **linearly with radius**. It is zero at the centre and maximum at the outer surface.
- **Torsional rigidity** = GJ (torque per radian per unit length). **Torsional stiffness** = GJ/L.

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- **Hollow shaft** vs solid shaft of the **same weight (area) and material**: the hollow shaft carries **more torque** and is **stiffer**, because the material is placed where the stress is high. For the **same torque**, a hollow shaft is lighter.
- For a solid shaft, torque capacity ∝ **d^3** and stiffness ∝ **d^4**. Doubling d gives 8 times the strength and 16 times the stiffness.
- Shafts in **series**: the same torque passes through each, and the angles of twist add ($\theta = \theta_1 + \theta_2$). Shafts in **parallel**: the angle of twist is the same, and the torques add ($T = T_1 + T_2$).
- **Combined bending and torsion**: equivalent BM $M_e = \frac{1}{2}[M + \sqrt{(M^2 + T^2)}]$. Equivalent torque $T_e = \sqrt{(M^2 + T^2)}$.

KEY FORMULAE – TORSION

- Torsion equation: **$T/J = \tau/r = G\theta/L$** (θ in radians)
- Solid shaft: $J = \pi d^4/32$; $T = (\pi/16)\,\tau\, d^3$; polar modulus $Z_p = \pi d^3/16$.
- Hollow shaft: $J = \pi(D^4 - d^4)/32$; $T = (\pi/16)\,\tau\,(D^4 - d^4)/D$.
- Power: **$P = 2\pi NT/60$** watts (N in rpm, T in N·m). In kW: $P = 2\pi NT/60\,000$.
- Thin tube (mean radius R, thickness t): $T = 2\pi R^2 t\tau$.
- Maximum shear stress from bending and torsion: $\tau_{max} = (16/\pi d^3)\sqrt{(M^2 + T^2)}$.

Columns & Struts

- **Column** = a vertical compression member. **Strut** = an inclined or horizontal compression member (as in trusses). **Post/pillar/stanchion** are other names.
- **Short column** fails by **crushing**. **Long column** fails by **buckling**. Intermediate columns fail by a combination of both.
- **Slenderness ratio** $\lambda = L_e/k_{min}$, using the **least radius of gyration**. The column buckles about the axis with the **minimum I**.
- IS 456: a column is **short if $L_e/D < 12$** ($L_e/D \geq 12$ means slender). Maximum unsupported length ≤ 60 × least lateral dimension. IS 800: maximum λ = **180** for compression members carrying dead and imposed loads; **250** for compression members resisting wind/seismic forces only; **350** for ties (roof truss/bracing) that face reversal only from wind or seismic loads; **400** for tension members.
- **Euler's assumptions**: the column is initially **perfectly straight**, the load is **exactly axial**, the material is homogeneous and elastic, self-weight is ignored, and failure is by buckling only.
- **Limitation of Euler's formula**: it is valid only when the crippling stress ≤ the proportional limit, i.e. for **long columns**. For mild steel this means $\lambda \geq$ about **80–90** ($\lambda_{lim} = \pi\sqrt{(E/f_y)} \approx 89$ for $f_y = 250$ and $E = 2 \times 10^5$). For short columns Euler's formula gives an unrealistically high load ($P \to \infty$ as $\lambda \to 0$).
- **Rankine–Gordon formula** is empirical and valid for **all lengths**, since it combines crushing and buckling.

End conditions	Theoretical L_e	IS 800 / IS 456 recommended L_e	Euler load (relative to both ends hinged)
Both ends hinged	**L**	1.0 L	**$1 \times (\pi^2EI/L^2)$**
One end fixed, other free	**2L**	2.0 L	**1/4**
One end fixed, other hinged	**$L/\sqrt{2} \approx 0.707L$**	0.80 L	**2**
Both ends fixed	**L/2**	0.65 L	**4**

- Ratio of Euler loads: fixed–free : hinged–hinged : fixed–hinged : fixed–fixed = **1 : 4 : 8 : 16**.
- The IS values are larger than the theoretical ones because **perfect fixity cannot be achieved** in practice.

KEY FORMULAE – COLUMNS

- Euler's crippling load: **$P_e = \pi^2EI / L_e^2$**. Euler stress $\sigma_e = \pi^2E / \lambda^2$.
- Rankine–Gordon: **$1/P_R = 1/P_c + 1/P_e$**, so $P_R = \sigma_c A / [1 + a(L_e/k)^2]$, with $a = \sigma_c/(\pi^2E)$.
- Rankine constants: mild steel σ_c = **320 N/mm², a = 1/7500**; cast iron 550, 1/1600; wrought iron 250, 1/9000; timber 40, 1/750.
- Eccentrically loaded short column: $\sigma = (P/A)(1 \pm 6e/b)$ for a rectangle. There is **no tension when e ≤ b/6** (the middle-third rule). For a circular section, e ≤ **d/8**, i.e. a core of diameter d/4.
- Secant formula (eccentric long column): $\sigma_{max} = (P/A)[1 + (e\,y_c/k^2)\sec((L_e/2)\sqrt{(P/EI)})]$.

MEMORY TRICK

"**Free = 2, Fixed = ½**". For effective length, cantilever columns double and fixed–fixed columns halve. Euler load varies as $1/L_e^2$, so the loads go **1 : 4 : 8 : 16**. Kern (middle third) for a rectangle is b/6 each side. For a circle the core diameter is d/4 (e = d/8).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Effective length of a column fixed at one end and free at the other → **2L**.
- Ratio of the Euler load of a fixed–fixed column to a hinged–hinged column → **4**.
- Euler's formula is valid for → **long columns** (crippling stress below the proportional limit).
- Power transmitted by a shaft → **$2\pi NT/60$**.
- Same weight: which is stronger in torsion? → **Hollow shaft**.
- No tension in a rectangular column if eccentricity ≤ → **b/6**.

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1.9 Principal Stresses, Mohr's Circle & Theories of Failure ★★★

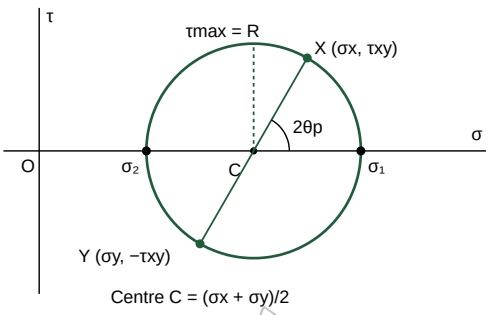
- **Principal planes** are the planes on which the **shear stress is zero**. The normal stresses on them are the **principal stresses**, which are the maximum and minimum normal stresses. There are 2 principal planes in 2-D (3 in 3-D), **mutually perpendicular**.
- Planes of maximum shear stress are at **45°** to the principal planes. Unlike principal planes, they carry a normal stress of $(\sigma_x + \sigma_y)/2$.
- **Complementary shear stresses**: a shear stress on one plane is always accompanied by an **equal shear stress on the perpendicular plane**. This is needed for moment equilibrium.
- Sum of normal stresses on any two perpendicular planes is **constant** ($\sigma_x + \sigma_y = \sigma_1 + \sigma_2$). This is the first **stress invariant**.

KEY FORMULAE

- Normal stress on a plane at θ: $\sigma_n = (\sigma_x + \sigma_y)/2 + [(\sigma_x - \sigma_y)/2] \cos 2\theta + \tau_{xy} \sin 2\theta$
- Principal stresses: $\boldsymbol{\sigma_{1,2} = (\sigma_x + \sigma_y)/2 \pm \sqrt{\{[(\sigma_x - \sigma_y)/2]^2 + \tau_{xy}^2\}}}$
- Principal planes: $\tan 2\theta_p = 2\tau_{xy} / (\sigma_x - \sigma_y)$
- Maximum in-plane shear: $\boldsymbol{\tau_{max} = (\sigma_1 - \sigma_2)/2} = \sqrt{\{[(\sigma_x - \sigma_y)/2]^2 + \tau_{xy}^2\}}$
- Uniaxial σ: on a plane at θ to the cross-section, $\sigma_n = \sigma \cos^2\theta$ and $\tau = (\sigma/2) \sin 2\theta$. $\tau_{max} = \boldsymbol{\sigma/2}$ **at 45°**.
- Pure shear τ: $\sigma_1 = +\tau$, $\sigma_2 = -\tau$, on planes at **45°**.
- Beam (σ from bending, τ from shear): $\sigma_{1,2} = \sigma/2 \pm \sqrt{[(\sigma/2)^2 + \tau^2]}$.

Mohr's Circle – Facts

- Centre = $\boldsymbol{((\sigma_x + \sigma_y)/2, 0)}$. Radius = $\boldsymbol{\tau_{max}} = (\sigma_1 - \sigma_2)/2$.
- An angle **θ on the element** corresponds to **2θ on Mohr's circle**.
- Where the circle cuts the σ-axis gives σ_1 and σ_2. The top and bottom points give τ_{max}.
- **Equal biaxial stress** ($\sigma_x = \sigma_y$, $\tau = 0$), including hydrostatic stress: the circle is a **point**, so the radius is 0 and **τ = 0 on every plane**.
- **Pure shear**: the circle is **centred at the origin** with radius τ.
- **Uniaxial tension**: the circle passes through the origin, with radius σ/2.
- Mohr's circle for strain has ε on the horizontal axis and **γ/2** on the vertical axis.



Mohr's circle: centre at the mean normal stress, radius = τ_{max}. The intercepts on the σ-axis are the principal stresses. Angles on the circle are double those on the element.

Theories of Failure

Theory	Failure criterion	Suitable for	Yield locus (σ_1–σ_2 plane)
Maximum principal stress – Rankine	$\sigma_1 = f_y$	**Brittle** materials	Square
Maximum principal strain – St. Venant	$\sigma_1 - \nu(\sigma_2 + \sigma_3) = f_y$	Brittle (not suitable for ductile)	Rhombus
Maximum shear stress – Guest / Tresca (Coulomb)	$(\sigma_1 - \sigma_3)/2 = f_y/2$	**Ductile**; gives the most conservative (safe) design	**Hexagon**
Total strain energy – Haigh (Beltrami)	$\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1) = f_y^2$	Ductile (fairly good)	Ellipse
Maximum distortion (shear strain) energy – von Mises (Hencky)	$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2f_y^2$	**Ductile – best agreement with tests**	**Ellipse** (circumscribes the Tresca hexagon)

- Shear yield stress in pure shear: Tresca $\tau_y = \mathbf{0.5\ f_y}$; von Mises $\tau_y = \mathbf{f_y/\sqrt{3} = 0.577\ f_y}$; Rankine $\tau_y = f_y$; St. Venant $\tau_y = f_y/(1 + \nu)$.
- IS 800:2007 uses the **von Mises** value: design shear strength is based on $f_y/\sqrt{3}$.
- Under **hydrostatic stress**, the distortion energy and maximum shear theories predict **no failure**.
- For uniaxial loading, **all theories give the same result**.

MEMORY TRICK

"**Ra-Ve brittle, Gu-Mi ductile**": RAnkine and Saint VEnant for brittle materials; GUest (Tresca) and von MIses for ductile ones. Shapes: Rankine **Square**, Tresca **Hexagon**, von Mises **Ellipse** ("S-H-E").

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- Shear stress on principal planes → **Zero**.
- Angle between the principal plane and the plane of maximum shear → **45°**.
- Radius of Mohr's circle represents → **maximum shear stress**.
- Mohr's circle for equal biaxial tension → **a point**.
- Best theory of failure for ductile materials → **Maximum distortion energy (von Mises)**.
- Yield locus of the maximum shear stress theory → **Hexagon**.

1.10 Thin & Thick Cylinders, Springs ★★☆

- **Thin cylinder**: the wall is thin compared with the diameter, so stress is taken as **uniform** through the thickness. Usually **t < d/20** (d/t > 20). Radial stress is neglected.
- **Hoop (circumferential) stress** σ_h = pd/(2t). This is the **largest** stress, so failure occurs along a **longitudinal joint** (the cylinder splits lengthwise). **Longitudinal stress** σ_L = pd/(4t) acts on the circumferential joints.
- σ_h = **2** σ_L. Longitudinal joints are made stronger: double-riveted or butt-welded, or made with higher efficiency.
- With joint efficiency η: $\sigma_h = pd/(2t\eta_L)$, where η_L is the longitudinal joint efficiency. $\sigma_L = pd/(4t\eta_c)$, where η_c is the circumferential joint efficiency.
- **Thin sphere**: stress = **pd/(4t)** in all directions. It is half the hoop stress of a cylinder of the same d and t. So a sphere needs **half the thickness** of a cylinder.
- **Thick cylinder – Lamé's theory**: radial and hoop stresses vary across the wall. $\sigma_r = B/r^2 - A$ and $\sigma_h = B/r^2 + A$, with compressive σ_r taken as positive. **Hoop stress is maximum at the inner surface**. Radial stress = p at the inner surface and 0 at the outer surface (for internal pressure only). Both vary **hyperbolically** (as $1/r^2$) across the wall. The longitudinal stress (closed ends) is **uniform**.
- Thick cylinder, internal pressure p, radii r_1 (inner) and r_2 (outer): $\sigma_{h,max} = \mathbf{p(r_2^2 + r_1^2)/(r_2^2 - r_1^2)}$ at r_1. Even an infinitely thick wall cannot make $\sigma_{h,max}$ less than p.
- **Compound cylinders** (shrink fit) and **autofrettage** are used to even out the hoop stress across the wall.

KEY FORMULAE – THIN SHELLS

- Cylinder: σ_h = **pd/2t**; σ_L = **pd/4t**; maximum in-plane shear = $(\sigma_h - \sigma_L)/2$ = **pd/8t**.
- Hoop strain $\varepsilon_h = (pd/2tE)(1 - \nu/2)$. Longitudinal strain $\varepsilon_L = (pd/2tE)(½ - \nu)$.
- Volumetric strain (cylinder) = $2\varepsilon_h + \varepsilon_L$ = **(pd/4tE)(5 – 4v)**. Change in volume $\delta V = \varepsilon_v \times V$.
- Sphere: σ = **pd/4t**; volumetric strain = 3ε = **(3pd/4tE)(1 – v)**.
- For v = 0.5, the longitudinal strain of a thin cylinder is zero.

Springs

- **Close-coiled helical spring** under axial load: the wire is subjected mainly to **torsion** (direct shear and bending are neglected).
- **Open-coiled helical spring**: the wire is under **combined bending and torsion**.
- **Leaf (laminated, carriage) spring**: the plates are under **bending**. It is designed as a **beam of uniform strength**.
- **Stiffness** k = load per unit deflection (N/mm). Spring index C = D/d (mean coil diameter / wire diameter).
- Cutting a spring into two equal halves (half the turns n) **doubles** the stiffness of each half, since $k \propto 1/n$.
- **Wahl's correction factor** $K = (4C - 1)/(4C - 4) + 0.615/C$. It allows for curvature and direct shear.

KEY FORMULAE – SPRINGS

- Close-coiled spring (mean coil radius R, n turns, wire diameter d): $\tau = \mathbf{16WR/(\pi d^3)}$.
- Deflection: $\delta = \mathbf{64WR^3n/(Gd^4) = 8WD^3n/(Gd^4)}$.
- Stiffness: $\mathbf{k = Gd^4/(64R^3n) = Gd^4/(8D^3n)}$.
- Strain energy: U = ½Wδ.
- Springs in **series** (same load): $\mathbf{1/k = 1/k_1 + 1/k_2}$. Two equal springs give k/2.
- Springs in **parallel** (same deflection): $\mathbf{k = k_1 + k_2}$. Two equal springs give 2k.
- Semi-elliptic leaf spring (span L, n plates, b × t): $\sigma = \mathbf{3WL/(2nbt^2)}$; $\delta = \mathbf{3WL^3/(8Enbt^3)}$.
- Quarter-elliptic (cantilever) leaf spring: $\sigma = 6WL/(nbt^2)$; $\delta = 6WL^3/(Enbt^3)$.

Item	Thin cylinder	Thin sphere
Maximum stress	Hoop, pd/2t	pd/4t (equal in all directions)
Failure along	Longitudinal joint	Any diametral plane
Volumetric strain	(pd/4tE)(5 – 4v)	(3pd/4tE)(1 – v)
Thickness needed for the same p, d, σ	t	**t/2**

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Ratio of hoop stress to longitudinal stress in a thin cylinder → **2 : 1**.
- A thin cylinder under internal pressure tends to fail along → **the longitudinal joint** (by hoop stress).
- Where is the hoop stress maximum in a thick cylinder? → **At the inner surface**.
- Stiffness of two equal springs (k each) in series → **k/2**.
- Stiffness of a close-coiled spring varies as → $\mathbf{d^4 / (D^3 n)}$.
- A close-coiled helical spring wire under axial load is mainly under → **torsion**.

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2. Structural Analysis & Engineering Materials

NOTE

Two halves of one high-scoring chapter. In Structural Analysis, questions come from degree of indeterminacy, standard fixed-beam and propped-cantilever values, carry-over and distribution factors, ILD ordinates, arch thrust and shape factors, and nearly all of them can be answered from memorised results. In Building Materials (bricks, stones, lime, timber, paints, glass) the questions are short fact recall. Expect **8–12 MCQs** from this chapter.

2.1 Determinacy & Stability ★★★

- **Static indeterminacy (D_s)** = number of unknown forces (reactions + internal forces) − number of independent equilibrium equations. It is also the number of **redundants**.
- **Kinematic indeterminacy (D_k)** = number of unknown independent **joint displacements** (translations + rotations), also called degrees of freedom.
- Equilibrium equations available: **3 per body in a plane** (ΣF_x, ΣF_y, ΣM), **6 in space**.
- Support reactions in a plane: roller or link = **1**, hinge (pin) = **2**, fixed = **3**, guided roller (slider that resists rotation) = **2**. In space a fixed support has **6** and a ball-and-socket joint has **3**.
- **External indeterminacy** = r − 3 for a plane structure. **Internal indeterminacy** = D_s − external. A closed ring or closed frame is internally indeterminate to degree **3** per closed loop.
- **Releases (r_r)**: an internal hinge joining *n* members gives **n − 1** releases. A hinge in a beam gives **1**. An internal roller or link gives **2**.
- Stability: $D_s < 0$ means the structure is **unstable (a mechanism)**. $D_s \geq 0$ is **necessary but not sufficient**. The structure is **geometrically unstable** if all reactions are **parallel** or **concurrent**, even when r ≥ 3.
- Truss with m = 2j − 3 is a **perfect truss**, m < 2j − 3 is **deficient** (unstable), and m > 2j − 3 is **redundant**.
- Indeterminate structures need **compatibility** and **material (stress–strain) properties** in addition to equilibrium. Temperature change, lack of fit and support settlement cause stresses **only in indeterminate structures**.

Structure	D_s (static)	D_k (kinematic)
Plane (2-D) truss	**m + r − 2j**	**2j − r**
Space (3-D) truss	**m + r − 3j**	**3j − r**
Plane rigid frame	**3m + r − 3j − r_r**	**3j − r** (+ extra rotations at hinges; − m if members are axially rigid)
Space rigid frame	**6m + r − 6j − r_r**	**6j − r**
Plane frame (closed-loop method)	**3C − r_r** (C = number of closed loops, with the ground taken as one body)	–
Beam (general loading)	**r − 3 − r_r**	Count free displacements

- Notation: m = members, j = joints (supports count as joints), r = support reactions, r_r = releases.

Beam	D_s	D_k (axial deformation neglected)
Simply supported / cantilever	0	SS: **2** (θ_A, θ_B); cantilever: **2** (δ, θ at free end), or 3 if axial is counted
Propped cantilever	**1**	**1** (θ at prop)
Fixed beam	**3** (2 if there is no axial load)	**0**
Continuous beam, n spans, pinned/roller ends	**n − 1**	n + 1 rotations
Two-hinged arch / three-hinged arch / fixed arch	**1 / 0 / 3**	–

MEMORY TRICK

"**3 for plane, 6 for space; 2 for a plane truss joint, 3 for a space truss joint.**" D_s is always *(forces per member × m) + r − (equations per joint × j)*. D_k runs the other way: (DOF per joint × j) − r.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Degree of static indeterminacy of a fixed beam under transverse load only? → **2** (3 when axial force is included).
- Kinematic indeterminacy of a fixed–fixed beam? → **Zero**.
- A plane truss has 9 members, 6 joints and 3 reactions. D_s? → 9 + 3 − 12 = **0** (determinate).
- Releases at an internal hinge where 3 members meet? → **2**.
- Structure with all reactions concurrent? → **Geometrically unstable**.
- Single closed rectangular frame (box) with no supports: internal D_s? → **3**.

2.2 Energy Methods & Influence Lines ★★★

- **Strain energy**: axial $U = P^2L/2AE$; bending $U = \int M^2dx/2EI$; torsion $U = T^2L/2GJ$; shear $U = \int kV^2dx/2GA$. Strain energy per unit volume = $\sigma^2/2E$.
- **Castigliano's first theorem**: $\partial U/\partial \Delta_i = P_i$. It applies to non-linear elastic material as well.

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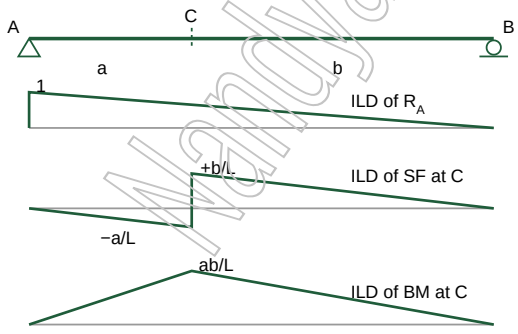
- **Castigliano's second theorem**: $\partial U/\partial P_i = \Delta_i$ (deflection in the direction of P_i). For rotation use $\partial U/\partial M = \theta$. It needs **linear elastic** behaviour.
- **Theorem of least work** (Menabrea's theorem, a corollary of Castigliano II): $\partial U/\partial R = 0$ for each redundant. Use it to analyse indeterminate structures. It does **not** apply directly when there is support settlement or lack of fit.
- **Unit load method** (virtual work, Maxwell–Mohr): $\delta = \int Mm\,dx/EI$ for beams and frames, and $\delta = \Sigma\, PkL/AE$ for trusses (k = force due to a unit load). Apply a unit moment to find a slope.
- **Maxwell's reciprocal theorem** (1864): $\delta_{ij} = \delta_{ji}$. The deflection at i due to a unit load at j equals the deflection at j due to a unit load at i. This makes **flexibility and stiffness matrices symmetric**.
- **Betti's law** (1872): the virtual work of load system P through the displacements caused by Q equals the work of Q through the displacements caused by P. **Maxwell's theorem is a special case of Betti's law.** Both need linear elastic structures with unyielding supports.
- Other deflection methods: double integration, **Macaulay's** (discontinuous loads), **moment-area** (Mohr's theorems), **conjugate beam** (a fixed end becomes free, a free end becomes fixed, an internal hinge becomes an internal support), strain energy and unit load.
- **Influence line diagram (ILD)**: shows how a response (reaction, SF, BM, deflection) at a **fixed section** varies as a **unit load moves** across the span. A BMD shows the moment at all sections for a **fixed** load. Ordinate × load gives the effect. For a UDL, effect = w × **area of the ILD** under the load.
- **Müller-Breslau principle** (1886): the ILD of any force function equals the **deflected shape** obtained by removing the restraint for that function and applying a **unit displacement** in its direction. ILDs of **determinate** structures are **straight-line** segments. ILDs of **indeterminate** structures are **curved**. The principle is based on Betti's law.



ILDs for a simply supported beam (C at distance a from A; L = a + b). The two SF lines are parallel with a total jump of 1 at C.

ILD (SS beam, section C at a from A)	Shape	Key ordinate
Reaction R_A	Triangle	**1** at A, 0 at B
Shear at C	Two parallel lines	**−a/L** just left, **+b/L** just right; jump = 1
BM at C	Triangle, apex at C	**ab/L** (L/4 at mid-span)
R_A of a cantilever (fixed at A)	Rectangle	1 throughout
BM at fixed end of a cantilever	Triangle	−L at the free end

Rolling load case (SS beam, span L)	Maximum BM at section C	Absolute maximum BM
Single point load W	W ab/L (load at C)	**WL/4** at mid-span
UDL w longer than span	w ab/2 (whole span loaded)	**$wL^2/8$** at mid-span
UDL shorter than span (length l)	When C divides the load in the **same ratio** as it divides the span	At mid-span, with the load centred on it
Train of point loads	When a load is at C and the **average load on the left of C = average load on the whole span**	Under a load (usually the heaviest, nearest the resultant) placed so that **mid-span bisects the distance between that load and the resultant**

KEY FORMULAE

- UDL longer than span: maximum +ve SF at C = **$w\,b^2/2L$** (load from C to B). Maximum −ve SF = **$w\,a^2/2L$**. Absolute maximum SF = **wL/2** at the support.
- Two equal loads W at spacing d: absolute maximum BM = **$W(L - d/2)^2/2L$**. This is valid when d < 0.586L. Otherwise a single load governs with WL/4.
- Deflection by unit load: $\delta = \Sigma\int Mm\,dx/EI$; truss: $\delta = \Sigma\, PkL/AE$.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- ILDs of statically determinate structures consist of? → **Straight lines**.
- Maximum ordinate of the ILD for BM at mid-span of an SS beam? → **L/4**.
- Which theorem is the basis of the Müller-Breslau principle? → **Betti's law** (Maxwell's reciprocal theorem).
- $\partial U/\partial P = \Delta$ is? → **Castigliano's second theorem**.
- Absolute maximum BM due to a moving UDL longer than the span? → **$wL^2/8$** at mid-span.
- Theorem that makes the flexibility matrix symmetric? → **Maxwell's reciprocal theorem**.

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2.3 Indeterminate Structures – Classical Methods ★★★

Fixed beam (span L)	Fixed-end moment	Mid-span BM	Maximum deflection
Central point load W	**WL/8** each end	+WL/8	**$WL^3/192EI$**
UDL w over full span	**$wL^2/12$** each end	+$wL^2/24$	**$wL^4/384EI$**
Eccentric point load W (a from A, b from B)	M_A = **Wab^2/L^2**, M_B = **Wa^2b/L^2**	–	–
Triangular load (0 at A, w at B)	M_A = **$wL^2/30$**, M_B = **$wL^2/20$**	–	–
Sinking of one support by Δ	**$6EI\Delta/L^2$** at both ends	–	–
Rotation θ at end A only	M_A = 4EIθ/L, M_B = 2EIθ/L	–	–
Couple M applied at mid-span	**M/4** at each end	–	0 at centre

- Points of contraflexure in a fixed beam: for a central point load at **L/4** from each end; for a UDL at **0.211L** from each end.
- A fixed beam is **stiffer** (central deflection is 1/5 of the SS value for a UDL and 1/4 for a point load), but it is sensitive to support settlement and temperature.

Propped cantilever (fixed at A, prop at B)	Prop reaction	Fixed-end moment	Other
UDL w	**3wL/8**	**$wL^2/8$**	Maximum +BM = **$9wL^2/128$** at 3L/8 from the prop; point of contraflexure at L/4 from the fixed end
Central point load W	**5W/16**	**3WL/16**	BM under load = **5WL/32**

- Two equal-span continuous beam with UDL: central support moment = **$wL^2/8$**; reactions = **3wL/8, 5wL/4, 3wL/8**. Three equal spans with UDL: interior support moments ≈ **$wL^2/10$**.

KEY FORMULAE

- **Clapeyron's three-moment equation** (1857), constant EI: $M_AL_1 + 2M_B(L_1 + L_2) + M_CL_2 = -(6A_1\bar{x}_1/L_1 + 6A_2\bar{x}_2/L_2)$. A = area of the free (SS) BMD; $\bar{x}_1$ is measured from A and $\bar{x}_2$ from C.
- 6Aẋ/L terms: UDL = **$wL^3/4$**; central point load = **$3WL^2/8$**.
- **Slope-deflection** (G.A. Maney, 1915): $M_{AB} = M_{FAB} + (2EI/L)(2\theta_A + \theta_B - 3\Delta/L)$.
- Stiffness (moment to rotate the near end by unit θ): far end fixed = **4EI/L**; far end hinged = **3EI/L**; symmetric case = 2EI/L; antisymmetric case = 6EI/L.
- Carry-over factor: far end fixed = ½; far end hinged = **0**.
- Distribution factor DF = k/Σk; **ΣDF at a joint = 1**. DF is 0 for a fixed-end member and 1 at a hinged end.
- Translational (sway) stiffness: both ends fixed = **$12EI/L^3$**; one end fixed and the other pinned = **$3EI/L^3$**.

- **Moment distribution method**: **Hardy Cross** (1930). It is an iterative **displacement** method with relaxation, the balancing of unbalanced moments. Frames that can sway need a **sway correction**.
- **Kani's method** (Gaspar Kani, 1947): iterative and **self-correcting**, so an error is eliminated in later cycles. Rotation factor = **−½ (k/Σk)**. Displacement factor for a storey = **−3/2 (k/Σk)**. Convenient for multi-storey frames.
- **Column analogy** (Hardy Cross): for fixed beams, closed frames and arches with up to **3 redundants**.

Feature	Flexibility (force) method	Stiffness (displacement) method
Primary unknowns	**Redundant forces**	**Joint displacements**
Number of equations	= D_s	= D_k
Equations used	**Compatibility**	**Equilibrium**
Classical examples	Consistent deformation, least work, three-moment, column analogy	Slope-deflection, moment distribution, Kani's
Matrix	[F], symmetric	[K] = $[F]^{-1}$, symmetric, positive diagonal
Computer use	Less suitable	**Preferred** (direct stiffness method, used in FEM)

- Beam element stiffness terms: $12EI/L^3$, $6EI/L^2$, 4EI/L, 2EI/L. Axial: AE/L. Torsion: GJ/L.
- **Stiffness** is the force needed for unit displacement. **Flexibility** is the displacement caused by a unit force. Each is the reciprocal of the other.

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MEMORY TRICK

Fixed-end moments "**8–12–30/20**": point load PL/**8**, UDL wL^2/**12**, triangle wL^2/**30** (light end) and wL^2/**20** (heavy end). Deflections "**192–384**": the UDL value is double the point-load denominator. Moment distribution "**4-3, ½-0**": stiffness 4 and 3, carry-over ½ and 0.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Carry-over factor for a prismatic member with the far end fixed? → **½**.
- Stiffness of a member with the far end hinged? → **3EI/L**.
- Prop reaction of a propped cantilever under UDL? → **3wL/8**.
- Moment distribution method is a? → **Displacement method** (Hardy Cross).
- Fixed-end moment due to sinking Δ of one support? → **6EIΔ/L^2**.
- Self-correcting iterative method of frame analysis? → **Kani's method**.

2.4 Arches, Cables & Plastic Analysis ★★☆

- **Three-hinged arch**: two springing hinges and one crown hinge. It is **statically determinate**, so temperature change and settlement cause no stresses.
- **Two-hinged arch**: D_s **= 1** (H is the redundant). A temperature rise **increases** H. Rib shortening **reduces** H. **Fixed (hingeless) arch**: D_s = 3.
- Parabolic arch under UDL over the full span: **BM = 0 everywhere**, so the arch carries pure compression. This holds for both the three-hinged and the two-hinged arch.
- **Linear arch (line of thrust)**: the funicular shape for the given loading. It is a **parabola for a UDL** and a polygon for point loads.
- **Eddy's theorem**: BM at any section of an arch = H × the **vertical intercept** between the linear arch (theoretical arch) and the centre line of the actual arch.
- Normal thrust and radial shear in a parabolic arch: N = H cos θ + V sin θ; S = V cos θ − H sin θ (θ = slope of the arch axis).
- **Cables** carry **tension only** (zero flexural stiffness). Under a UDL on the horizontal span the shape is a **parabola**. Under self-weight along the length it is a **catenary**. Minimum tension = H, at the **lowest point**. Maximum tension is at the **supports**.
- Anchor cable over a **guide pulley**: tension is the same on both sides, and the pier gets bending. Over a **saddle on rollers**: the horizontal components are equal and the pier gets **only a vertical force**.

KEY FORMULAE

- Three-hinged parabolic arch with UDL w over the whole span, rise h: **H = wL^2/8h**, V = wL/2.
- Three-hinged arch with a central point load W: H = **WL/4h**. Two-hinged parabolic arch with a central point load: H = **25WL/128h**.
- Equation of a parabolic arch: $y = 4hx(L - x)/L^2$.
- Cable with UDL and central dip d: H = **wL^2/8d**; $T_{max} = \sqrt{(H^2 + V^2)} = (wL/2)\sqrt{(1 + L^2/16d^2)}$.
- Parabolic cable length ≈ **$L + 8d^2/3L$**.

- **Plastic hinge**: a section that has yielded fully at the **plastic moment $M_p = f_y Z_p$** and rotates freely at constant moment.
- **Plastic neutral axis** = the **equal-area axis**, which divides the section into two equal areas. It coincides with the elastic NA only for doubly symmetric sections.
- **Shape factor** $S = Z_p/Z_e = M_p/M_y$. **Load factor** = collapse load/working load = **S × factor of safety**.
- Rectangle: $Z_e = bd^2/6$ and Z_p = **bd^2/4**, so S = 1.5.
- Number of plastic hinges for complete collapse = D_s **+ 1**. Independent mechanisms = **N − D_s** (N = possible hinge locations). Types of mechanism: **beam, sway (panel), gable, joint**, and combined.
- Theorems: **upper-bound (kinematic or mechanism) theorem** gives a load ≥ the true collapse load. **Lower-bound (static) theorem** gives a load ≤ the true collapse load. The **uniqueness theorem** holds when both are satisfied.

Section	Shape factor
Rectangle	**1.5**
Solid circle	**1.7** (16/3π = 1.698)
Thin-walled circular tube	1.27 (4/π)
I-section (major axis)	**1.12–1.15**
Diamond (square bent about a diagonal)	**2.0**
Triangle (base horizontal)	**2.34** (highest of the common sections)

Beam and load	Collapse load	Hinges
Cantilever, point load at free end	$W_c = M_p/L$	1 (at support)
SS beam, central point load	$W_c = 4M_p/L$	1
SS beam, UDL	$w_c = 8M_p/L^2$	1
Propped cantilever, central point load	$W_c = 6M_p/L$	2
Propped cantilever, UDL	$w_c = 11.656M_p/L^2$; sagging hinge at 0.414L from the prop	2
Fixed beam, central point load	$W_c = 8M_p/L$	3

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Fixed beam, UDL	$w_c = 16M_p/L^2$	3
Fixed beam, eccentric point load (a, b)	$W_c = 2M_pL/ab$	3

MEMORY TRICK

Collapse loads under a point load run "**4 – 6 – 8**" (SS, propped, fixed) × M_p/L. Under a UDL they run "**8 – 11.66 – 16**" × M_p/L^2. Shape factors in increasing order: "**I(1.14) < Rect(1.5) < Circle(1.7) < Diamond(2) < Triangle(2.34)**".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Shape factor of a rectangular section? → **1.5**. Of a diamond section? → **2.0**.
- Horizontal thrust of a three-hinged parabolic arch under UDL? → **$wL^2/8h$**.
- Collapse load of a fixed beam with UDL? → **$16M_p/L^2$**.
- BM at any section of an arch is proportional to the intercept between the actual arch and the linear arch (theorem name)? → **Eddy's theorem**.
- The mechanism method gives a load that is? → An **upper bound** (≥ true collapse load).
- Shape of a cable under a UDL over the horizontal span? → **Parabola**.

2.5 Bricks & Clay Products ★★★

- Code: **IS 1077:1992**, common burnt clay building bricks. Tests: **IS 3495 (Parts 1–4):1992** for compressive strength, water absorption, efflorescence and warpage. Brickwork code: **IS 2212:1991**.
- **Modular size** = **190 × 90 × 90 mm** (and 190 × 90 × 40 mm). The **nominal size** with a 10 mm mortar joint is **200 × 100 × 100 mm**. The traditional (non-modular) size is about 230 × 110 × 70 mm (9″ × 4½″ × 3″).
- Tolerance is checked on 20 bricks laid together: length **3800 ± 80 mm**, width and height (90 mm bricks) **1800 ± 40 mm**.
- **Frog**: an indentation of about **100 × 40 × 10 mm** in 90 mm high bricks. It forms a key for mortar, reduces weight and carries the maker's mark. It is **not provided in 40 mm** high bricks. Lay bricks with the **frog upward**.
- About **500 modular bricks per m^3** of brickwork. Unit weight of brick masonry is about **19 kN/m^3**. One brick weighs about 3–3.5 kg.
- **Classes (IS 1077)**, by average compressive strength in N/mm^2: **35, 30, 25, 20, 17.5, 15, 12.5, 10, 7.5, 5 and 3.5**. Class 10 means ≥ 10 N/mm^2.
- **Water absorption** (24 h immersion in cold water): not more than **20%** by weight up to class 12.5, and **15%** for higher classes.
- **Efflorescence**: not more than **"moderate"** up to class 12.5, and **"slight"** for higher classes. It is caused by **soluble salts (alkalis)** that crystallise on the surface.
- Traditional classification: **first class** ≥ 10.5 N/mm^2 (water absorption ≤ 20%), **second class** ≥ 7 N/mm^2 (≤ 22%), **third class** ≥ 3.5 N/mm^2 (≤ 25%). **Over-burnt bricks (jhama)** are used as **aggregate or road metal**.
- Compression test: fill the frog with **1:1 cement mortar**, store under damp sacks for 24 h, immerse in water for 3 days, then load at **14 N/mm^2 per minute**.
- Field tests: a **clear metallic ringing** sound when two bricks are struck; **no impression** when scratched with a fingernail; **no breakage** when dropped from about 1 m onto hard ground; a uniform colour.
- **Heavy-duty bricks** (IS 2180:1988): ≥ **40 N/mm^2**, water absorption ≤ 10%. Perforated bricks: IS 2222. Fly-ash lime bricks: IS 12894:2002. Burnt clay fly-ash bricks: IS 13757:1993.

Efflorescence grade	Deposit
Nil	Imperceptible
Slight	≤ **10%** of exposed area, thin deposit
Moderate	**10–50%** of area, no powdering or flaking
Heavy	> **50%** of area, no powdering or flaking
Serious	Heavy deposit with **powdering and/or flaking**

Constituent of brick earth	Proportion	Role / effect of excess
Silica	**50–60%**	Prevents shrinkage, cracking and warping, and gives uniform shape. Excess makes bricks **brittle**.
Alumina	**20–30%**	Gives **plasticity** for moulding. Excess causes **shrinkage, cracking and warping** on drying.
Lime	≤ 5% (finely divided)	Acts as a flux and reduces shrinkage. Excess melts and distorts the brick. **Lumps of lime are harmful** (they slake and split the brick).
Iron oxide	5–6%	Gives the **red colour** and acts as a flux. Excess gives a dark blue colour.
Magnesia	≤ 1%	Yellow tint; reduces shrinkage.
Harmful	–	Lime lumps, **iron pyrites** (disintegration), **alkalis** (efflorescence, fusion), pebbles and vegetable matter.

- Manufacture: preparation of clay (unsoiling, digging, cleaning, **weathering**, blending, **tempering** in a **pug mill**), then moulding (hand: ground or table; or machine: plastic clay or dry press), then drying, then burning.
- Burning: dehydration at 400–650°C, oxidation at 650–900°C, and **vitrification at about 900–1100°C**. The final burning temperature is about **1000–1100°C**.

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Kiln	Type	Key fact
Clamp	Intermittent, **temporary**	Small output; bricks are unevenly burnt; cheap.
Up-draught / down-draught kiln	Intermittent, permanent	Down-draught gives more uniform burning.
Bull's trench kiln	**Continuous**, trench in the ground, **no permanent roof**	**Most common in India**; cannot work in the monsoon.
Hoffman's kiln	**Continuous**, circular plan, about 12 chambers, **permanent roof**	Works in all seasons; good-quality bricks; high initial cost.
Tunnel kiln	Continuous	Bricks move on cars through a fixed fire zone; best control.

Bond	Arrangement	Remarks
English bond	**Alternate courses** of headers and stretchers	**Strongest**; a **queen closer** is placed next to the quoin header; no continuous vertical joints.
Flemish bond	Headers and stretchers **alternate in every course**	Better appearance but weaker than English bond. **Double Flemish**: both faces Flemish. **Single Flemish**: Flemish face with English backing.
Stretcher bond	All stretchers	Half-brick (10 cm) **partition walls**.
Header bond	All headers	**Curved walls** and footings.
Rat-trap bond	Bricks **on edge**, leaving a cavity	Economical (saves about 25% bricks); thermal insulation.
Raking bond (diagonal, herring-bone)	Inclined bricks	Thick walls, between face courses.
Garden-wall bond	Mostly stretchers (3 or 5 per header)	Boundary walls up to 2 m.

- **Queen closer** = a brick cut **lengthwise** into two halves (half width). **King closer** = one corner cut off (half header, full stretcher). **Bat** = a brick cut **across its width** (half bat, ¾ bat).
- **Refractory (fire) bricks**: from fire clay, which is rich in alumina and silica with few fluxes. They withstand about **1600°C+**. **Acid**: fire clay and **silica** bricks. **Basic**: **magnesite**, dolomite and bauxite. **Neutral**: **chromite**, chrome-magnesite and carborundum.
- **Clay tiles**: **Mangalore pattern** roofing tiles (IS 654); flooring tiles (IS 1478); **terracotta** is hollow, lightweight, ornamental burnt clay; stoneware and porcelain are vitrified and non-porous. **Salt glazing** is used for stoneware drain pipes.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Standard modular size of a brick? → **190 × 90 × 90 mm**.
- Constituent that gives plasticity to brick earth? → **Alumina**. That causes efflorescence? → **Alkalis**.
- Maximum water absorption of a brick up to class 12.5 (IS 1077)? → **20%**.
- Strongest bond in brickwork? → **English bond**.
- Continuous kiln with a permanent roof? → **Hoffman's kiln**.
- Efflorescence covering 10–50% of the surface is graded? → **Moderate**.

2.6 Stones, Lime & Mortar ★★☆

Geological class	Formation	Examples
Igneous (physically unstratified)	Cooling of magma	**Granite** (plutonic), **basalt and trap** (volcanic), dolerite
Sedimentary (physically stratified)	Deposition of sediments	**Sandstone, limestone**, shale, laterite, gypsum, dolomite
Metamorphic (physically foliated)	Heat and pressure on existing rocks	**Marble** (from limestone), **quartzite** (from sandstone), **slate** (from shale), **gneiss** (from granite), schist

- Chemical classes: **siliceous** (granite, quartzite, sandstone), **argillaceous** (clay-based: slate, laterite), **calcareous** ($CaCO_3$: marble, limestone).
- A good building stone has specific gravity **> 2.7**, water absorption **< 5%** (24 h), and crushing strength **> 100 N/mm²**. Granite: about 100–250 N/mm².
- Uses: **granite** for bridge piers, dams and heavy works; **marble** for ornamental and flooring work (Makrana marble, used in the Taj Mahal); **slate** for roofing and DPC; **laterite** for building blocks (Kerala, Konkan; hardens on exposure); **red sandstone** (Red Fort).
- Lay stone with its **natural bed perpendicular to the load**, which means horizontal in walls and **radial in arches**. In cornices the bed is vertical.
- **Quarrying**: excavation for soft stone; **heating**; **wedging** for soft stratified stone; **blasting** for hard stone. Explosives: gunpowder (blasting powder), dynamite, gun-cotton and cordite. Tools: jumper, tamping bar, priming needle, scraping spoon. Blasting acts along the **line of least resistance**.
- **Seasoning**: remove the **quarry sap** by exposure for 6–12 months. Dress stone **before** seasoning, while it is soft.
- **Dressing finishes**: hammer-dressed, rough-tooled, punched, boasted, **chisel-drafted margin**, rubbed, polished and **vermiculated** (worm-track pattern).
- **Ashlar masonry**: finely dressed blocks with joints **≤ 3 mm**. **Rubble masonry**: coursed, uncoursed, random or polygonal. Provide **through (bond) stones** about every 1.5 m.

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Test on stone	Purpose
Attrition test (Deval)	Resistance to **wear and abrasion** (road stone)
Crushing test	Compressive strength
Smith's test	Presence of **soluble earthy or clayey matter** (water turns cloudy)
Acid test	Weathering resistance and presence of **$CaCO_3$** in sandstone (1% HCl)
Brard's test / crystallisation test	**Frost resistance** and durability (sodium sulphate)
Hardness test (Dorry's), impact test (Page)	Hardness and toughness
Water absorption, freeze–thaw	Porosity and durability

- **Lime cycle**: limestone $CaCO_3$ is **calcined** at about 900°C to give **quicklime CaO** + CO_2. Quicklime is **slaked** with water to give **slaked (hydrated) lime Ca(OH)$_2$**, which **sets by carbonation** (absorbing CO_2) back to $CaCO_3$.
- **Fat lime** (high-calcium, rich or white lime): clay < 5%. It slakes vigorously and its volume increases **2–2½ times**. It sets slowly **in air only** (carbonation). Used for plastering and white-washing, not in damp or underwater work.
- **Hydraulic lime**: clay **5–30%**. It sets **under water** (hydration of silicates and aluminates). Grades: **feebly** (5–10% clay; sets in about 3 weeks), **moderately** (11–20%; 1–2 weeks), **eminently** (21–30%; about 1 day). **Kankar** is an impure nodular limestone that yields hydraulic lime.
- **Poor (lean) lime**: impurities > 30%. It slakes slowly and makes poor mortar.
- **IS 712** building lime classes: **A** eminently hydraulic, for structural work; **B** semi-hydraulic, for masonry mortar; **C** fat lime, for finishing coats and white-wash; D magnesium lime; E kankar lime; F siliceous dolomitic lime.
- Field tests on lime: heat test, **acid test** (effervescence shows carbonate), ball test, workability test.

Mortar / use	Usual mix
Ordinary load-bearing brickwork	CM **1:6** (1:4 for heavier loads or more storeys)
Ceiling plaster	CM **1:3** (about 6 mm)
Internal wall plaster	CM 1:6 (12 mm on the fair side, 15 mm on the rough side)
External plaster / water-retaining structures	CM **1:4** / 1:3
Pointing	CM **1:2 or 1:3**
Lime mortar	Lime : sand = 1:2 to 1:3
Composite (gauged) mortar	Cement : lime : sand = 1:1:6, 1:2:9

- **IS 2250:1981** grades masonry mortars by 28-day strength: **H1 ≥ 10**, H2 7.5–10, **M1 5–7.5**, M2 3–5, M3 1.5–3, L1 0.7–1.5 and L2 0.5–0.7 N/mm².
- Use cement mortar **within 30 minutes** of adding water, before initial set. **Surkhi** (powdered burnt clay) is a pozzolana used with lime. **Grout** is fluid mortar. **Fire-resistant mortar**: aluminous cement with fire-brick powder.
- **Bulking of sand**: maximum at about **4–6% moisture** (20–40% increase in volume, more in fine sand). It is **zero for dry and for fully saturated sand**.
- **Gypsum** ($CaSO_4 \cdot 2H_2O$) heated to about **120–160°C** gives **plaster of Paris** ($CaSO_4 \cdot \frac{1}{2}H_2O$, hemihydrate). POP sets in **5–10 minutes** and **expands slightly** on setting. Heated above about 200°C it becomes **anhydrite** (dead-burnt). Gypsum is added to cement as a **retarder**. **Keene's cement** is anhydrous gypsum with alum and gives a hard, polished finish.

MEMORY TRICK

Metamorphic pairs as "parent → child": **Lime → Marble, Sand → Quartz(ite), Shale → Slate, Granite → Gneiss** ("L-M, S-Q, Sh-Sl, G-G"). Lime by clay %: **Fat < 5 < Feebly < 10 < Moderately < 20 < Eminently < 30 < Poor**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Marble is an example of? → **Metamorphic** rock (from limestone).
- Smith's test on stone detects? → **Soluble earthy/clayey matter**.
- Test for frost resistance of stone? → **Brard's (crystallisation) test**.
- Lime that sets under water? → **Hydraulic lime**.
- Chemical formula of plaster of Paris? → **$CaSO_4 \cdot \frac{1}{2}H_2O$**.
- Fat lime sets by? → **Carbonation** (CO_2 from air).

2.7 Timber ★★☆

- **Exogenous** trees grow **outward** and form **annual rings**, so they are used for engineering timber. They are of two kinds: **conifers (softwood)**, which have needle leaves, are resinous, light-coloured and have **indistinct medullary rays** (deodar, chir, pine, fir, kail); and **deciduous (hardwood)** trees, which are broad-leaved, dark, strong and have **distinct medullary rays** (teak, sal, shisham, oak, mahogany, babul).
- **Endogenous** trees grow **inward** (bamboo, palm, cane, coconut). They have limited structural use, except bamboo.
- Age of a tree = **number of annual rings**. Fell trees when they are mature and the sap is at rest: **mid-winter (plains)**, mid-summer (hills).
- **Teak** (Tectona grandis) is the most durable and termite-resistant. **Sal** (Shorea robusta) is hard and heavy and is used for sleepers. **Deodar** (Cedrus deodara) is the best Indian softwood. **Shisham** is used for furniture.

Part of an exogenous tree (centre outwards)	Description

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Pith (medulla)	Innermost core; decays first in old trees.
Heartwood (duramen)	Inner annual rings; dark, dead, **strong and durable**. This is the useful timber.
Sapwood (alburnum)	Outer rings; light-coloured, carries sap, weaker and decays easily.
Cambium layer	Thin layer between sapwood and bark that forms new wood. If exposed, the tree dies.
Inner bark (bast), outer bark (cortex)	Protection.
Medullary rays	**Radial** strands from pith to bark that **hold the annual rings together**.

- **Seasoning**: reducing moisture to about the **equilibrium moisture content**. Seasoned timber for joinery and furniture: about **10–12%**. Freshly felled timber: often > 30–50%. **Fibre saturation point**: about **25–30%**. Strength rises as MC falls below the FSP.
- Natural seasoning: **air seasoning** (slow, about 1–4 years, good quality) and **water seasoning** (logs in flowing water for 2–4 weeks wash out the sap). Artificial seasoning: boiling, **chemical (salt)**, **kiln seasoning** (compartment or progressive; most common industrially) and **electrical seasoning** (high-frequency AC; **quickest and costliest**).
- Sawing: **quarter sawing** (radial) gives the best figure and least shrinkage. Tangential (flat) sawing is cheaper.
- **Dry rot**: a fungus (*Merulius lacrymans*, now *Serpula lacrymans*) attacks timber in **poorly ventilated, damp** places and reduces it to a **dry powder**. **Wet rot**: caused by **alternate wetting and drying**; the tissue decomposes. Other agents: **termites** (white ants), beetles and marine borers.

Defect group	Examples (key meaning)
Natural	**Knots** (base of branches; dead, live, loose); **shakes**: **heart shake** (radial cracks from the pith; shrinkage of the heartwood in over-matured trees), **cup shake** (separation **between annual rings**), **star shake** (cracks **from the bark inward**; extreme heat or frost), ring shake, radial shake; twisted fibres (wandering heart); upsets (crushed fibres); rind galls; burls
Fungal	Blue stain, brown rot, white rot, heart rot, sap stain, dry rot, wet rot
Conversion	Chip mark, diagonal grain, torn grain, **wane** (original rounded surface left on the edge)
Seasoning	**Bow** (curvature along the length), **cup** (across the width), **twist** (spiral), **spring** (along the edge in its own plane), checks, splits, **honey-combing**, **case-hardening** (outer zone set in compression), collapse, warp
Others	**Druxiness** (white decayed spots), **foxiness** (reddish-brown stains from poor ventilation or over-maturity)

- **Preservatives** (IS 401:2001, code of practice for preservation of timber): coal tar (cheap, bad smell, cannot be painted); **creosote oil** (distilled from coal tar; very effective; used for **sleepers and piles**); **ASCU** (developed at FRI Dehradun: **1 part arsenic pentoxide + 3 parts copper sulphate + 4 parts sodium or potassium dichromate**; 6 parts are mixed in 100 parts of water; termite-proof, odourless and paintable); **CCA** (copper–chrome–arsenic); solignum paint (termites); and zinc chloride or copper sulphate.
- Methods: brushing, spraying, dipping and steeping, **charring** (the ends of posts to be buried), hot and cold open tank, and **pressure impregnation**, the most effective. Pressure processes are **full-cell (Bethell)** and empty-cell (Rueping, Lowry).
- **Fire retardancy**: **Abel's process** (sodium silicate coating) and ammonium phosphate.
- **Plywood**: an **odd number** of veneers (3, 5, 7…) glued with the **grain of adjacent veneers at right angles** (IS 303:1989; marine plywood IS 710:2010). Grades: **BWP** (boiling-water proof), BWR (boiling-water resistant), MR (moisture resistant). Veneer thickness is about 0.4–6 mm.
- **Block board / lamin board**: a core of wood strips between veneers. **Particle board** (chip board): wood chips bonded with synthetic resin (IS 3087). **Fibre board**: **hardboard** (high density, pressed) and insulation board (low density) (IS 1658); MDF. **Glulam**: glued laminated timber for large members. **Impreg / compreg**: resin-impregnated (compreg is also compressed).
- **Plank**: thickness < 50 mm and width > 150 mm. Timber is measured in **m^3**.
- **IS 883:2016** (design of structural timber) groups timber by modulus of elasticity: **Group A** > 12.6, **B** 9.8–12.6, **C** 5.6–9.8 kN/mm^2. Timber is **strongest in tension parallel to the grain**. Compression parallel to the grain is much greater than perpendicular to it.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Age of a tree is found by counting? → **Annual rings**.
- Defect where separation occurs between annual rings? → **Cup shake**.
- Quickest method of seasoning? → **Electrical seasoning**.
- Composition of ASCU? → **As_2O_5 : $CuSO_4$: $Na_2Cr_2O_7$ = 1 : 3 : 4**.
- Plywood always has? → An **odd number of plies**.
- Decay of timber in an ill-ventilated, damp place, turning it to powder? → **Dry rot**.

2.8 Paints, Glass, Plastics, Bitumen & Other Materials ★★☆

Paint constituent	Function	Examples
Base	Body and **opacity**; forms the film	White lead, **red lead**, zinc white (zinc oxide), lithopone, titanium white, iron oxide

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Vehicle (carrier)	Binds the base; spreads and forms the film	**Linseed oil** (raw, boiled, double-boiled), tung, poppy and nut oil
Drier	Speeds up drying (oxidation of the oil)	**Litharge**, red lead, lead acetate, manganese dioxide, cobalt
Thinner (solvent)	Makes paint thin and workable; evaporates	**Turpentine**, naphtha, petroleum spirit, benzene
Pigment (colouring)	Colour	Lamp black (black), ochre (yellow), Prussian blue, chrome green, Venetian red, burnt umber (brown)
Inert filler (extender)	Reduces cost and adds bulk	Barytes, chalk, gypsum, silica

Paint / finish	Key fact
Oil paint	Oil-based; most common for wood and steel
Enamel	Pigment ground in varnish; **glossy** and hard
Emulsion	PVA or acrylic in water; quick-drying, washable, thinned with water
Cement paint	White cement + pigment + accelerator; for **exterior** surfaces; apply on a **damp** surface
Distemper	Chalk (whiting) + glue (size) + water. Cheap, for **interior** plastered walls. Dry distemper or oil-bound distemper (OBD).
Aluminium paint	Aluminium powder in spirit or oil varnish. **Visible in the dark** and heat-reflecting; used for **gas tanks, water pipes** and roofs.
Anti-corrosive paint	Oil + red lead / zinc chrome; **red lead primer** for steel; zinc chromate primer for aluminium
Bituminous paint	Black; for **iron work under water** and pipes
Cellulose paint	Nitro-cellulose; motor cars; hard and smooth
Asbestos paint, silicate paint	Fire resistance and leakage control

- **Varnish** = resin + solvent (no pigment). **Oil varnish**: hard resins such as amber or copal in linseed oil. **Spirit varnish**: **shellac (lac) in methylated spirit**, which is **French polish**. Turpentine varnish: mastic, dammar or rosin. Water varnish: shellac in hot water with borax.
- **Paint defects**: **blistering** (trapped moisture or vapour), **bloom** (dull patches), **chalking** (powdery surface), **flaking**, **grinning** (the background shows through because of poor opacity), **running and sagging** (thin paint on smooth vertical surfaces), **saponification** (soap formed by alkali in fresh plaster), **wrinkling** (a coat that is too thick), **alligatoring** (cracking into a pattern).
- Painting sequence: **priming coat → undercoat → finishing coat**. Primer for wood: **pink primer** (white lead + red lead).
- **Glass** is an **amorphous, super-cooled liquid** with no definite melting point. Typical composition: **silica about 70%**, soda about 15% and lime about 10%. **Annealing** (slow cooling) removes internal stresses.
- Colouring agents: **iron oxide or chromium → green**; cobalt → blue; manganese → violet; copper or selenium → red; **gold → ruby red**.

Glass	Key fact / use
Soda-lime (soft, crown) glass	Cheapest; **window panes** and bottles
Potash-lime (hard, Bohemian) glass	Higher fusion temperature; chemical apparatus
Potash-lead (flint) glass	High refractive index; **lenses, optical work**, artificial gems
Borosilicate (Pyrex)	**Low thermal expansion**; heat-resistant lab ware
Toughened (tempered)	Heated, then **rapidly cooled**; 4–5 times stronger; breaks into **small blunt granules**
Laminated (safety)	Glass layers with a **PVB interlayer**; holds together when broken; bullet-resistant when multi-layered
Wired glass	Wire mesh embedded; **fire-resisting**, skylights
Float glass	Molten glass floated on a **tin bath** (Pilkington process); the most common flat glass
Ground, frosted or obscured	Privacy
Foam glass, glass wool, fibre glass	Insulation; GFRP

Polymer type	Behaviour	Examples
Thermoplastics	Linear chains; **soften on heating and can be remoulded**; recyclable	**PVC**, polyethylene (LDPE, HDPE), polypropylene, polystyrene, **acrylic (Perspex)**, nylon, PTFE (Teflon)
Thermosetting	Cross-linked; **set permanently** and cannot be re-softened	**Bakelite** (phenol-formaldehyde, the first synthetic plastic, 1907), urea- and melamine-formaldehyde, **epoxy**, polyester, silicone

- Plastics are light, corrosion-resistant and good insulators. Their drawbacks are **low E, creep, high thermal expansion, poor fire resistance and UV degradation**. Uses: uPVC and CPVC (hot water) pipes, HDPE water mains, water tanks, sheets and adhesives.

Binder	Source	Key fact
Bitumen	**Residue of fractional distillation of petroleum**; natural lake or rock asphalt	Soluble in **carbon disulphide (CS_2)**. Grades: **VG-10, 20, 30, 40** (IS 73:2018); VG-30 is most used.

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Tar	**Destructive distillation** of coal or wood	More **temperature-susceptible**; better adhesion; contains more free carbon; soluble in toluene; carcinogenic
Asphalt	Bitumen + inert mineral matter	**Mastic asphalt**: bitumen + fine filler, laid hot, **voidless and impervious**; used for DPC, flat roofs and floors
Cutback	Bitumen + volatile solvent	**RC** (naphtha), **MC** (kerosene), **SC** (heavy oil)
Emulsion	Bitumen dispersed in water with an emulsifier	RS, MS, SS; usable in **wet weather**; patch work

- **Damp-proofing materials**: hot bitumen, **mastic asphalt**, bituminous felts, metal sheets (**lead**, copper, aluminium), stones (**slate**, granite), dense engineering bricks, cement concrete (1:2:4 or 1:1.5:3) or rich cement mortar with **integral waterproofing compounds**, and polythene sheets. See also 2.9.
- **Aluminium**: density **2.7 g/cm³**, about one-third of steel (7.85). E ≈ **70 GPa**, about one-third of steel. Thermal expansion ≈ 23 × 10^{-6}/°C, about **twice** that of steel. Melting point **660°C**. A protective **oxide film** (thickened by **anodising**) prevents corrosion. Ore: **bauxite**. **Duralumin** (Al + about 4% Cu + Mg + Mn) is used in aircraft. Used for windows, curtain walls, partitions and roofing sheets.
- Ferrous metals by carbon content: **wrought iron** < 0.15% (nearly pure); **mild steel** 0.1–0.25%; high-carbon steel up to about 1.5%; **cast iron 2–4.5%** (brittle, strong in compression). Zinc is used for **galvanising**. Lead is used for flashing and DPC.
- **Geosynthetics** are made mostly of **polypropylene, polyester and HDPE**. Their six functions are **separation, filtration, drainage, reinforcement, containment (barrier) and protection**.

Geosynthetic	Main function
Geotextile (woven / non-woven)	Permeable fabric: **separation, filtration**, drainage, reinforcement
Geogrid	Open apertures (uniaxial or biaxial): **reinforcement** of soil walls and pavement bases
Geomembrane	**Impermeable barrier**: landfill and canal or pond liners
Geonet / geocomposite	**In-plane drainage**
Geocell	3-D honeycomb **confinement**: slopes, weak subgrade
GCL (geosynthetic clay liner)	Bentonite layer between geotextiles; barrier
Geofoam (EPS)	**Lightweight fill**

MEMORY TRICK

Paint ingredients in order "**B-V-D-T-P**": "**B**ig **V**ans **D**on't **T**ake **P**assengers", meaning Base, Vehicle, Drier, Thinner, Pigment. Remember "**Linseed is the Vehicle, Litharge the Drier, Turpentine the Thinner**".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Most common vehicle in oil paints? → **Linseed oil**.
- Thinner commonly used in paints? → **Turpentine**.
- French polish is a? → **Spirit varnish** (shellac in methylated spirit).
- Glass used for laboratory ware because of low thermal expansion? → **Borosilicate (Pyrex)**.
- Bitumen is completely soluble in? → **Carbon disulphide**.
- Example of a thermosetting plastic? → **Bakelite**.

2.9 Building Construction Essentials ★★☆

- **Foundations**: shallow ($D_f \le B$), which include isolated or spread, combined, strap (cantilever), strip and **raft (mat)**; and deep, which include **pile, pier and well (caisson)**. **Grillage** foundations use layers of steel joists for heavy column loads on poor soil. IS 1080:1985 requires a minimum depth of **50 cm** below natural ground. Rankine's minimum-depth formula and bearing capacity are covered in **Chapter 6**.
- **DPC** is laid at **plinth level** over the full wall width, at least 15 cm above ground. It is usually 25–40 mm of rich cement concrete (1:1.5:3 or 1:2:4) with a waterproofing compound, or bitumen or mastic asphalt. A **vertical DPC** is used for basement walls (tanking). Plinth height should be at least **45 cm** above the surrounding ground (NBC minimum).
- **Brick masonry**: soak bricks before laying; joints about **10 mm**; do not raise a wall more than about **1.5 m per day** (CPWD specification: 1 m); cure for at least **7 days**; keep perpends (vertical joints) in alternate courses in line. Stone ashlar joints are ≤ 3 mm.
- **Cavity wall**: two leaves with a **50–75 mm cavity** tied by wall ties. Gives thermal and sound insulation and keeps out damp.
- **Lintel** bearing is at least **15 cm** or the lintel depth, whichever is more. Masonry within an **equilateral triangle** (60°) above the opening is carried by the lintel, and the rest arches over it.
- **Arch terms**: **intrados** (inner curve), **extrados** (outer curve), **soffit** (inner surface), **voussoirs** (wedge units), **keystone** (central top voussoir), **skewback** (inclined surface on the abutment), springing, crown, haunch, spandrel, rise and span. A **relieving arch** is built over a lintel.
- **Expansion joints** in buildings are provided at about **45 m** maximum spacing (IS 456). **Anti-termite** treatment of soil before construction: IS 6313.

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Stair rule / limit	Value
Blondel's rule	**2R + T = 60 cm** (range 60–64 cm)
Other thumb rules	R + T = 40–45 cm; R × T ≈ 400–450 cm²
Usual residential riser / tread	About 15–17 cm / 25–30 cm
NBC 2016: maximum riser	**190 mm** (residential); **150 mm** (other buildings)
NBC 2016: minimum tread	**250 mm** (residential); **300 mm** (other buildings)
Maximum risers per flight	**15** (NBC); about 12 in standard texts. Minimum 3.
Headroom	≥ **2.2 m** (NBC); 2.1 m in older texts
Pitch of stair	About 25°–40°

- Stair types: straight; **dog-legged** (half-turn with **no well** between flights; economical for houses); **open-newel** (well) stair; quarter-turn; bifurcated (public buildings); **spiral or helical** (least floor space); geometrical. Parts: nosing, going, winder (tapered step), newel post, baluster, landing (width ≥ stair width).
- **Floors**: IPS (Indian patent stone: CC 1:2:4 topping 25–40 mm), terrazzo or mosaic (marble chips in white cement), granolithic, Kota stone, marble, vitrified or ceramic tiles, timber, magnesite. Jack-arch floors use steel joists with brick arches.
- **Pitched roofs by span**: lean-to (shed), couple roof up to about **3.6 m**, couple-close up to about 4.2 m, collar-beam roof, **king-post truss 5–8 m**, **queen-post truss 8–12 m**, steel trusses beyond that. **Mansard** roofs have two slopes on each side. Flat roofs: RCC, Madras terrace, jack arch, with a slope of about 1 in 100 for drainage. GI or AC sheets: end lap about 15 cm, side lap 1½ corrugations.
- **Doors**: ledged-braced-battened, framed and panelled, **flush**, glazed, collapsible (steel), **rolling shutter** (shops and godowns), revolving, swing. A typical external door is about 1.0 × 2.1 m, with width ≈ 0.4–0.6 × height. Frames are fixed with **holdfasts** (usually 3 per side). A **parliament hinge** lets the leaf open through 180°.
- **Windows**: casement, sash (double-hung), pivoted, sliding, louvered, **bay** (projecting outward), **dormer** (on a sloping roof), **clerestory** (high on a wall above an adjacent roof), lantern, skylight. Under NBC, window and ventilator area should be at least about **1/10 of the floor area**.
- **Plastering**: single coat **12 mm** (fair side) or 15 mm (rough side); two-coat external work about 20 mm; ceiling about 6 mm. Rake joints about 10–15 mm deep to form a key, and cure for **7 days**. Defects: blistering, cracking, **efflorescence**, peeling, **popping** (unslaked lime particles), rust stains. **Pointing** types: flush, recessed, **tuck**, V, weathered, beaded, struck, keyed.

NBC 2016 (Part 3) requirement	Minimum value
Habitable room area / width	**9.5 m²** / **2.4 m** (with two rooms, the second may be 7.5 m² with 2.1 m width)
Kitchen area / width	**5.0 m²** / 1.8 m
Bathroom / WC / combined bath + WC	**1.8 m²** (width 1.2 m) / **1.1 m²** (width 0.9 m) / **2.8 m²** (width 1.2 m)
Height of habitable room (floor to ceiling)	**2.75 m**; air-conditioned rooms 2.4 m
Height of bath, WC, store, garage	**2.2 m**
Kitchen height	2.75 m
High-rise building	Height ≥ **15 m**

- **Fire safety (NBC 2016 Part 4)**: occupancy groups **A** residential, **B** educational, **C** institutional, **D** assembly, **E** business, **F** mercantile, **G** industrial, **H storage (warehouses, which applies to CWC godowns)**, **J** hazardous.
- Construction types by fire resistance of structural elements: **Type 1 = 4 h, Type 2 = 3 h, Type 3 = 2 h, Type 4 = 1 h.**
- Fire-resistant materials: **brick is the best**; concrete is good (cover gives protection); **steel loses about half its strength at about 550–600°C** and needs fire protection; timber chars (a thick section resists better than a thin one); ordinary glass is poor (**wired glass** is better); asbestos is good.

MEMORY TRICK

NBC room sizes "**9.5 – 5 – 1.8 – 1.1**" (room, kitchen, bath, WC in m²) and heights "**2.75 – 2.4 – 2.2**" (habitable, AC, bath/WC). Stairs: "**190/250 home, 150/300 elsewhere**".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Thumb rule relating rise and tread? → **2R + T = 60 cm**.
- Minimum floor-to-ceiling height of a habitable room (NBC 2016)? → **2.75 m**.
- Minimum area of a habitable room (NBC)? → **9.5 m²** with a minimum width of 2.4 m.
- DPC is generally provided at? → **Plinth level**.
- Top central wedge-shaped unit of an arch? → **Keystone**.
- NBC occupancy group of a warehouse? → **Group H (Storage)**.

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3. Concrete Structures, Design & IS Codes

> **NOTE**
> RCC design is the single biggest scoring block in civil MCQs: expect **6–10 questions** on IS 456:2000 numbers – partial safety factors, $x_{u,max}/d$, $M_{u,lim}$, cover, τ_{bd}, span/depth ratios, column steel limits and footing critical sections. Questions are almost always "direct value" type, so memorise the tables in this chapter. All clause numbers refer to **IS 456:2000 (fourth revision, with amendments)** unless stated otherwise.

3.1 Design Philosophies & IS 456:2000 General ★★★

Feature	Working Stress Method (WSM)	Ultimate Load Method (ULM)	Limit State Method (LSM)
Basis	Elastic theory; stresses at **service** load	Ultimate strength; collapse load	Probabilistic; **collapse + serviceability**
Safety provided by	**Factor of safety on material stress** (permissible stress)	**Load factor** on loads	**Partial safety factors** on both loads (γ_f) and materials (γ_m)
Stress–strain	Linear (straight line)	Non-linear (actual)	Non-linear (parabolic-rectangular)
Drawback	Uneconomical; ignores creep/shrinkage, true failure	Ignores serviceability (large deflection, cracks)	— (most rational)
IS 456 location	**Annex B**	Not in IS 456:2000 (was in IS 456:1964 as "load factor method")	**Section 5** (cl 35–44)

- **Limit state** = a state of impending failure beyond which the structure is no longer fit for use.
- Two groups: **Limit state of collapse** (flexure, compression, shear, torsion, overturning/sliding) and **Limit state of serviceability** (deflection, cracking, vibration, durability).
- **Characteristic strength** (cl 35.1) = strength below which **not more than 5%** of test results are expected to fall → $f_{ck} = f_m - 1.65\,s$.
- **Characteristic load** = load that has **95% probability of not being exceeded** during the life of the structure.
- Design strength = f_k/γ_m; Design load = $\gamma_f \times$ characteristic load.
- Concrete grade = characteristic compressive strength of **150 mm cube at 28 days** in N/mm² (M20 → f_{ck} = 20 N/mm²).
- Grades (Table 2): **Ordinary M10–M20; Standard M25–M55; High strength M60–M80.**
- **Minimum grade for RCC = M20** (cl 6.1.2, Table 5 mild exposure). PCC – no minimum for mild exposure; **M15** for moderate.
- **Modulus of elasticity** (short-term static): $E_c = 5000\sqrt{f_{ck}}$ N/mm² (cl 6.2.3.1). M20 → 22,360 N/mm²; M25 → 25,000 N/mm².
- **Flexural strength** (modulus of rupture): $f_{cr} = 0.7\sqrt{f_{ck}}$ (cl 6.2.2).
- E_s for all steel = 2×10^5 **N/mm²** (cl 5.6.3).
- Total shrinkage strain ≈ **0.0003** (cl 6.2.4.1). Creep coefficient: **2.2 (7 days), 1.6 (28 days), 1.1 (1 year)** loading age (cl 6.2.5.1).
- Unit weight: **PCC 24 kN/m³, RCC 25 kN/m³** (IS 875 Part 1).
- Max cement content (OPC, excluding fly ash/GGBS) = **450 kg/m³** (cl 8.2.4.2).
- Min curing (moist) = **7 days OPC**; **10 days** when mineral admixtures/blended cements are used (and 10 days in hot weather) (cl 13.5.1).

Partial safety factor for MATERIALS γ_m (cl 36.4.2, Table 18 notes)		
Material	**Limit state of collapse**	**Serviceability**
Concrete	**1.5**	1.0
Steel	**1.15**	1.0
Accidental loads (collapse)	Concrete **1.3**, steel **1.0**	—

Load combination	Limit state of COLLAPSE (Table 18)			SERVICEABILITY		
	DL	IL	WL/EL	DL	IL	WL/EL
DL + IL	**1.5**	**1.5**	—	1.0	1.0	—
DL + WL	**1.5 or 0.9***	—	**1.5**	1.0	—	1.0
DL + IL + WL	**1.2**	**1.2**	**1.2**	1.0	**0.8**	**0.8**

- *__0.9__ is used for DL when dead load **contributes to stability** (overturning/uplift check). Earthquake load (EL) replaces WL in the same combinations.
- Design strength of steel = $f_y/1.15$ = **0.87 f_y**; design stress of concrete in flexure = 0.67 $f_{ck}/1.5$ = **0.446 f_{ck}** (≈ 0.45 f_{ck}). The 0.67 converts cube strength to in-situ member strength.

Exposure (Table 3)	Plain concrete (PCC)			Reinforced concrete (RCC)			Nomi cover (Table 16)
	Min cement kg/m³	Max w/c	Min grade	Min cement kg/m³	Max w/c	Min grade	
Mild	220	0.60	—	**300**	**0.55**	**M20**	**20 m**
Moderate	240	0.60	M15	300	0.50	**M25**	**30 m**
Severe	250	0.50	M20	320	0.45	**M30**	**45 m**
Very severe	260	0.45	M20	340	0.45	**M35**	**50 m**

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Extreme	280	0.40	M25	360	0.40	**M40**	**75 mm**

- Exposure definitions: **Mild** – protected against weather (except coastal); **Moderate** – sheltered from severe rain, buried in non-aggressive soil, **continuously under water**; **Severe** – alternate wetting & drying, **completely immersed in sea water**, coastal environment; **Very severe** – **sea-water spray**, corrosive fumes, aggressive sub-soil; **Extreme** – **tidal zone**, direct contact with aggressive chemicals.
- Cover notes (Table 16): for bars **≤ 12 mm** in mild exposure, cover may be reduced by **5 mm**; for severe & very severe, 5 mm reduction allowed if grade ≥ **M35**; tolerance on cover **+10 mm / 0 mm**.
- Nominal cover ≥ **bar diameter** always. Columns: ≥ **40 mm** (or 25 mm for columns of min. dimension ≤ 200 mm with bars ≤ 12 mm). Footings: ≥ **50 mm** (cl 26.4.2).
- Max chloride content (Table 7, as Cl^- kg/m³): prestressed **0.4**; RCC **0.6**; PCC without embedded metal **3.0**. Total water-soluble sulphate (SO_3) ≤ **4%** by mass of cement.

Nominal cover (mm) for FIRE resistance – Table 16A (simply supported / continuous)

Fire rating	0.5 h	1 h	1.5 h	2 h	3 h	4 h
Beams	20/20	20/20	20/20	40/30	60/40	70/50
Slabs	20/20	20/20	25/20	35/25	45/35	55/45
Columns	**40 mm for all ratings**					

MEMORY TRICK

Exposure ladder "**Mild-Moderate-Severe-Very severe-Extreme**" → RCC grade **20-25-30-35-40** (step 5), cover **20-30-45-50-75**, w/c **0.55-0.50-0.45-0.45-0.40**, cement **300-300-320-340-360**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Partial safety factor for steel at limit state of collapse? → **1.15**.
- Characteristic strength is the strength below which not more than ___ results fall? → **5%**.
- E_c of M25 concrete as per IS 456? → **25,000 N/mm²** (5000√25).
- Nominal cover for "severe" exposure? → **45 mm**.
- Load factor for DL+LL+WL combination (collapse)? → **1.2**.
- Minimum grade of RCC in moderate exposure? → **M25**.

3.2 Working Stress Method ★★☆

- Assumptions: plane sections remain plane; **concrete in tension ignored**; linear stress–strain for both materials; **perfect bond**; modular ratio m used to transform steel to equivalent concrete.
- **Modular ratio m = 280 / (3 σ_{cbc})** (Annex B-1.3) – partially accounts for **long-term creep**. M20 → m = 280/21 = **13.33**; M15 → 18.67; M25 → 10.98; M30 → 9.33.
- For compression steel in beams use **1.5 m** (to allow for creep).
- Permissible stresses may be increased by **33⅓%** when wind or earthquake is combined (B-2.3); redistribution of moments limited to **15%** in WSM (vs 30% in LSM).

Permissible stresses in concrete (N/mm²) – Table 21

Grade	M15	M20	M25	M30	M35	M40
Bending σ_{cbc}	5.0	**7.0**	8.5	10.0	11.5	13.0
Direct σ_{cc}	4.0	**5.0**	6.0	8.0	9.0	10.0
Bond τ_{bd} (plain bars, tension)	0.6	0.8	0.9	1.0	1.1	1.2
$\tau_{c,max}$ (Table 24)	1.6	1.8	1.9	2.2	2.3	2.5

- σ_{cbc} for M10 = 3.0, M45 = 14.5, M50 = 16.0 N/mm² (rises by 1.5 per grade above M25).

Permissible stresses in steel (N/mm²) – Table 22

Type of stress	Mild steel Fe 250	HYSD Fe 415	HYSD Fe 500
Tension σ_{st}	**140** (≤ 20 mm φ); **130** (> 20 mm)	**230**	**275**
Compression in column bars σ_{sc}	130	190	190

Section type (WSM)	Condition	What reaches permissible stress first
Balanced	$x = x_c$ (critical NA)	Concrete and steel **simultaneously**
Under-reinforced	$x < x_c$	**Steel** first → ductile, gives warning (preferred)
Over-reinforced	$x > x_c$	**Concrete** first → brittle, sudden

KEY FORMULAE (WSM, SINGLY REINFORCED)

- Actual NA: $\mathbf{b\,x^2/2 = m\,A_{st}\,(d - x)}$ (moment of areas about NA).
- Critical NA factor $\mathbf{k = m\,\sigma_{cbc} / (m\,\sigma_{cbc} + \sigma_{st})}$; $x_c = k\,d$.
- Lever arm factor **j = 1 – k/3**; Moment of resistance $M = ½\,\sigma_{cbc}\,k\,j\,b\,d^2 = \mathbf{R\,b\,d^2}$, $R = ½\,\sigma_{cbc}\,k\,j$.
- Since $m\,\sigma_{cbc} = 280/3 =$ **93.33 always**, k depends **only on σ_{st}**, not on concrete grade.
- Fe 250 (σ_{st} 140): **k = 0.40**, j = 0.867; Fe 415 (230): **k = 0.289**, j = 0.904; Fe 500 (275): k = 0.253, j = 0.916.
- M20 + Fe 415: R = 0.5 × 7 × 0.289 × 0.904 ≈ **0.91**; M20 + Fe 250: R ≈ **1.21** N/mm².
- Steel stress from actual NA: $\sigma_{st} = m\,\sigma_c\,(d - x)/x$.

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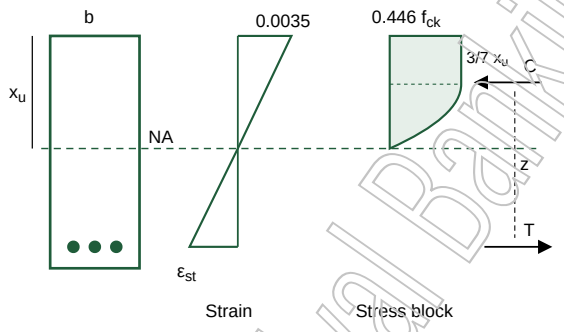
PREVIOUSLY ASKED / LIKELY QUESTIONS

- Modular ratio for M20 concrete? → **13.33**.
- Permissible tensile stress in Fe 415 (WSM)? → **230 N/mm²**.
- σ_{cbc} for M25? → **8.5 N/mm²**.
- Neutral axis depth factor for balanced section with mild steel (σ_{st} = 140)? → **0.40**.
- In an under-reinforced section, failure initiates by? → **Yielding of steel**.

3.3 Limit State of Collapse – Flexure ★★★

- Assumptions (cl 38.1): plane sections remain plane (strain linear); **max compressive strain in concrete in bending = 0.0035**; tensile strength of concrete **ignored**; concrete stress–strain **parabolic up to 0.002, then rectangular** to 0.0035 with design peak **0.446 f_{ck}**; steel design stress = 0.87 f_y; **tensile strain in steel at failure ≥ 0.87 f_y/E_s + 0.002**.
- Strain limits: pure axial compression **0.002**; bending **0.0035**; whole section in compression → 0.0035 − 0.75 × strain at least compressed fibre (cl 39.1).
- Minimum steel strain at failure: Fe 250 = 0.0031 ($0.87\times250/2\times10^5$ + 0.002 ≈ 0.00309); **Fe 415 = 0.0038**; Fe 500 = 0.00418.
- Stress block: rectangular portion = top **3/7 x_u**; parabolic portion = **4/7 x_u** above NA.
- Over-reinforced design is **not permitted** in LSM; if $x_u > x_{u,max}$ → increase depth or design as **doubly reinforced**.



LSM stress block (cl 38.1): C = 0.36 f_{ck} b x_u acting 0.42 x_u from top; T = 0.87 f_y A_{st}; lever arm z = d − 0.42 x_u.

Steel	f_y (N/mm²)	$x_{u,max}/d$ (cl 38.1)	$M_{u,lim}/(f_{ck}\ b\ d^2)$	$p_{t,lim}$ for M20 (%)	Min. steel strain
Fe 250	250	**0.53**	**0.148**	1.76	0.0031
Fe 415	415	**0.48**	**0.138**	0.96	0.0038
Fe 500	500	**0.46**	**0.133**	0.76	0.0042

- $x_{u,max}/d$ = 0.0035 / (0.0055 + 0.87 f_y/E_s) – higher f_y → **smaller** $x_{u,max}/d$.
- $M_{u,lim}$ depends on f_{ck} and steel grade, but the **coefficient** depends only on steel grade.

KEY FORMULAE (LSM, ANNEX G)

- Total compression C = **0.36 f_{ck} b x_u**, located at **0.42 x_u** from compression face.
- Equilibrium: 0.36 f_{ck} b x_u = 0.87 f_y A_{st} → **x_u = 0.87 f_y A_{st} / (0.36 f_{ck} b)**.
- M_u = 0.87 f_y A_{st} (d − 0.42 x_u) = **0.87 f_y A_{st} d [1 − A_{st} f_y / (b d f_{ck})]**.
- $M_{u,lim}$ = 0.36 ($x_{u,max}/d$)(1 − 0.42 $x_{u,max}/d$) f_{ck} b d^2 → **0.138 f_{ck} b d^2** (Fe 415).
- $p_{t,lim}$ = 41.61 (f_{ck}/f_y)($x_{u,max}/d$) %.
- **Doubly reinforced**: $M_u - M_{u,lim}$ = (f_{sc} − f_{cc}) A_{sc} (d − d′); A_{st} = A_{st1} + A_{st2}, A_{st2} = (f_{sc} − f_{cc})A_{sc} /0.87 f_y, with f_{cc} = 0.446 f_{ck}.
- f_{sc} for Fe 250 = **217.5 N/mm²** (yields for all d′/d); for Fe 415 with d′/d = 0.10 ≈ **353 N/mm²** (from strain compatibility, SP 16).

Steel limits in beams (cl 26.5.1)	Value
Minimum tension steel	**$A_s/(b\ d)$ = 0.85/f_y** (Fe 415 → 0.205%; Fe 250 → 0.34%)
Maximum tension steel	**0.04 b D** (4% of gross)
Maximum compression steel	**0.04 b D**
Compression bars to be enclosed by	Stirrups (as for column ties) to prevent buckling
Side-face steel	D > **750 mm** → **0.1%** of web area, both faces, spacing ≤ 300 mm or web thickness

Flanged beams (T & L)

Beam	Effective flange width b_f (cl 23.1.2)
T-beam (monolithic)	**$b_f = l_0/6 + b_w + 6\ D_f$**
L-beam (monolithic)	**$b_f = l_0/12 + b_w + 3\ D_f$**
Isolated T-beam	$b_f = l_0/(l_0/b + 4) + b_w$
Isolated L-beam	$b_f = 0.5\ l_0/(l_0/b + 4) + b_w$

- l_0 = distance between points of **zero moment** (≈ **0.7 × effective span** for continuous beams); b = actual width of flange; b_f must not exceed the actual width available.
- If $x_u \le D_f$ → NA in flange → design as **rectangular beam of width b_f**.
- NA in web, $D_f/d \le 0.2$: M_u = 0.36($x_{u,max}/d$)(1 − 0.42$x_{u,max}/d$) f_{ck} b_w d^2 + **0.45 f_{ck}($b_f - b_w$) D_f(d − D_f/2)**.
- If $D_f/d > 0.2$, replace D_f by **y_f = 0.15 x_u + 0.65 D_f** (≤ D_f).
- Transverse reinforcement in flange ≥ **60%** of main span steel of slab (cl 23.1.1 b) when slab steel is parallel to beam.
- Lateral stability (cl 23.3): simply supported/continuous beam – clear distance between lateral restraints ≤ **60 b or**

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250 b²/d (lesser); cantilever ≤ **25 b or 100 b²/d**.

- Deep beam (cl 29): l/D < **2.0** (simply supported), < **2.5** (continuous).
- Moment redistribution in LSM up to **30%**, with $x_u/d \le 0.6 - \delta M/100$ (cl 37.1.1).

MEMORY TRICK

"**53-48-46** and **148-138-133**": as steel goes 250 → 415 → 500, $x_{u,max}/d$ falls 0.53 → 0.48 → 0.46 and $M_{u,lim}$ coefficient falls 0.148 → 0.138 → 0.133. Stress block "**36-42**": force 0.36, location 0.42.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Max compressive strain in concrete in bending (LSM)? → **0.0035**.
- $x_{u,max}/d$ for Fe 500? → **0.46**.
- Depth of centroid of compressive force from top? → **0.42 x_u**.
- Minimum tension steel in beams (Fe 415)? → **0.85 b d/f_y ≈ 0.205%**.
- Effective flange width of T-beam? → **$l_0/6 + b_w + 6D_f$**.
- Side face reinforcement is required when depth exceeds? → **750 mm**.

3.4 Shear, Bond, Torsion & Development Length ★★★

- **Nominal shear stress $\tau_v = V_u/(b\ d)$** (cl 40.1); for varying depth, $V_u \pm (M_u/d) \tan \beta$.
- **τ_c** (Table 19) = design shear strength of concrete; depends on **grade and $p_t = 100\ A_s/(b\ d)$** (tension steel continuing at least d beyond section).
- Critical section for shear = **d from face of support** (when support reaction causes compression in end region, cl 22.6.2).
- Enhanced shear near supports: within 2d of support τ_c may be taken as **$2d\ \tau_c/a_v$** (cl 40.5).
- If **$\tau_v > \tau_{c,max}$** → section must be **redesigned** (increase size), shear steel cannot help.

τ_c for M20 (N/mm²) – Table 19 (selected)

p_t %	≤ 0.15	0.25	0.50	0.75	1.00	1.50	2.00	≥ 2.50
τ_c	0.28	0.36	0.48	0.56	**0.62**	0.72	0.79	0.82

Maximum shear stress $\tau_{c,max}$ (LSM) – Table 20

Grade	M15	M20	M25	M30	M35	M40 & above
$\tau_{c,max}$ (N/mm²)	2.5	**2.8**	3.1	3.5	3.7	**4.0**

Condition	Shear reinforcement required
$\tau_v < 0.5\ \tau_c$ (minor members like lintels)	None needed
$\tau_v \le \tau_c$	**Minimum shear reinforcement** (cl 26.5.1.6)
$\tau_c < \tau_v \le \tau_{c,max}$	Design shear reinforcement for **$V_{us} = V_u - \tau_c\ b\ d$**
$\tau_v > \tau_{c,max}$	**Redesign section**
Solid slabs	$\tau_v \le k\ \tau_c$ – no stirrups; τ_v must not exceed **½ $\tau_{c,max}$** (cl 40.2.3.1)

KEY FORMULAE – SHEAR (CL 40.4)

- Vertical stirrups: **$V_{us} = 0.87\ f_y\ A_{sv}\ d\ /\ s_v$**.
- Inclined stirrups/series of bent bars: $V_{us} = 0.87\ f_y\ A_{sv}\ d\ (\sin\alpha + \cos\alpha)/s_v$.
- Single bent-up bar (or group at one section): V_{us} = **$0.87\ f_y\ A_{sv} \sin\alpha$**.
- Minimum shear steel: **$A_{sv}/(b\ s_v) \ge 0.4/(0.87\ f_y)$**, f_y not to be taken > **415 N/mm²**.
- Max spacing of stirrups: **0.75 d** (vertical), **d** (inclined at 45°), and in no case > **300 mm**.
- Bent-up bars may contribute **not more than half** of the total shear reinforcement.
- Slab factor k (cl 40.2.1.1): D ≥ 300 mm → 1.00; 250 → 1.10; 200 → 1.20; ≤ 150 mm → **1.30**.
- τ_c empirical: $\tau_c = 0.85\sqrt{(0.8 f_{ck})}(\sqrt{(1+5\beta)} - 1)/(6\beta)$, $\beta = 0.8\ f_{ck}/(6.89\ p_t) \ge 1$.

Bond & development length (cl 26.2)

- Bond resistance comes from **adhesion, friction and mechanical bearing** (ribs of deformed bars).
- **Development length $L_d = \varphi\ \sigma_s\ /\ (4\ \tau_{bd})$**, $\sigma_s = 0.87\ f_y$ at collapse.
- τ_{bd} **increased by 60%** for **deformed bars** (IS 1786) and by a further **25%** for bars in **compression**.
- Bundled bars: L_d of each bar increased by **10% (2 bars), 20% (3 bars), 33% (4 bars)** in contact.

Design bond stress τ_{bd} (LSM) for PLAIN bars in tension (N/mm²)

Grade	M20	M25	M30	M35	M40 & above
Plain bars	**1.2**	1.4	1.5	1.7	1.9
Deformed (×1.6)	**1.92**	2.24	2.40	2.72	3.04

Case (M20)	L_d
Fe 250 plain bar, tension	**45.3 φ** (≈ 45φ)
Fe 415 deformed bar, tension	**47 φ**
Fe 415 deformed bar, compression	**37.6 φ** (≈ 38φ)
Fe 500 deformed bar, tension	**56.6 φ** (≈ 57φ)

- Anchorage value (cl 26.2.2.1): standard **U-hook = 16 φ**; bend = **4 φ per 45°** of bend, max 16 φ (so 90° bend = **8 φ**). Hooks/bends are **not effective in compression** – only straight projected length counts.
- At simple supports and points of inflection: **$L_d \le 1.3\ M_1/V + L_0$** (1.3 when ends confined by compressive reaction; 1.0 otherwise). L_0 at point of inflection limited to **d or 12φ**, greater.

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- At least **1/3 of positive steel** (simply supported) / **1/4** (continuous) to extend into support by $L_d/3$ (cl 26.2.3.3).

Lap splice (cl 26.2.5.1)	Lap length
Flexural tension	L_d **or 30 φ**, whichever greater
Direct tension	**2** L_d **or 30 φ**, whichever greater
Compression	L_d **(compression) but ≥ 24 φ**
Straight length of lap	**≥ 15 φ or 200 mm**
Bars larger than **36 mm**	No lapping – **weld** instead
Different diameters	Lap based on **smaller** bar
Location	Away from max BM (where M > 50% M_R); not more than **half the bars** lapped at a section; laps staggered by **1.3 × lap length** (c/c)

Torsion (cl 41)

KEY FORMULAE – TORSION

- Equivalent shear: $V_e = V_u + 1.6\,T_u/b$; $\tau_{ve} = V_e/(b\,d) \le \tau_{c,max}$.
- Equivalent moment: $M_{e1} = M_u + M_t$, where $M_t = T_u(1 + D/b)/1.7$.
- If $M_t > M_u$: provide steel on compression face for $M_{e2} = M_t - M_u$.
- Two-legged closed stirrups: $A_{sv} = T_u\,s_v/(b_1\,d_1\,0.87f_y) + V_u\,s_v/(2.5\,d_1\,0.87f_y)$, but $\ge (\tau_{ve} - \tau_c)\,b\,s_v/(0.87\,f_y)$.
- Torsion stirrup spacing ≤ x_1, $(x_1 + y_1)/4$, **300 mm** (least). Stirrups must be **closed**. Side-face longitudinal bars for torsion when D > **450 mm**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- $\tau_{c,max}$ for M20 (LSM)? → **2.8 N/mm²**.
- Maximum spacing of vertical stirrups? → **0.75 d or 300 mm**, whichever less.
- Design bond stress for deformed bars in tension, M20? → **1.92 N/mm²** (1.2 × 1.6).
- Development length of Fe 415 bar in M20 (tension)? → **≈ 47 φ**.
- Anchorage value of a standard 90° bend? → **8 φ**.
- Equivalent shear due to torsion? → $V_u + 1.6\,T_u/b$.

3.5 Slabs ★★★

Feature	One-way slab	Two-way slab
Aspect ratio	$l_y/l_x > 2$ (or supported on two opposite sides only)	$l_y/l_x \le 2$, supported on all four sides
Main steel	Along **short span**; distribution steel along long span	Both directions (short-span bars placed **below**, larger moment)
Load transfer	One direction	Both directions; short span carries more
Design method	As beam of 1 m width	Rankine–Grashoff (simply supported, corners not held down – Table 27); Marcus / **Table 26** coefficients (restrained, corners held down)

Span/effective depth (cl 23.2.1) – spans up to 10 m	Basic ratio
Cantilever	**7**
Simply supported	**20**
Continuous	**26**
Span > 10 m	Multiply by **10/span (m)** (except cantilever – calculate deflection)
Two-way slabs, span ≤ 3.5 m, LL ≤ 3 kN/m² (span/overall depth)	Mild steel: SS **35**, continuous **40**; Fe 415: multiply by **0.8** → 28 & 32

- Modification factors: **tension steel** (Fig 4) – depends on p_t and service stress $f_s = 0.58\,f_y \times (A_{st,req}/A_{st,prov})$; **compression steel** (Fig 5) – increases ratio; **flanged beams** (Fig 6) – reduction factor, **0.8** for $b_w/b_f \le 0.3$.
- Effective span (cl 22.2): simply supported → **clear span + d or c/c of supports**, whichever **less**; cantilever → length to face of support + d/2.

Slab detailing rule	Value (IS 456)
Minimum steel (either direction, cl 26.5.2.1)	**0.12%** of gross area (HYSD); **0.15%** (mild steel)
Max bar diameter (cl 26.5.2.2)	**D/8** (D = overall slab thickness)
Max spacing – main bars (cl 26.3.3)	**3 d or 300 mm**, whichever less
Max spacing – distribution bars	**5 d or 450 mm**, whichever less
Torsion steel at corners (two-way, Annex D)	¾ of max mid-span steel, in 4 layers, over $l_x/5$ from edges; ½ where one edge is continuous
Middle strip / edge strip (Annex D)	Middle strip = ¾ of width; edge strip = **l/8** each side (edge strip gets only minimum steel)

BM & SF coefficients for continuous beams/slabs (Tables 12 & 13) – ≥ 3 spans differing ≤ 15%

Location	Dead load	Imposed load
BM near middle of end span	+1/12	+1/10
BM at middle of interior span	+1/16	+1/12
BM at support next to end support	**−1/10**	**−1/9**
BM at other interior supports	−1/12	−1/9
Shear at end support	0.40	0.45

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Shear at first interior support (outer side)	0.60	0.60

Flat slabs (cl 31)

- Flat slab = slab supported **directly on columns without beams**; with or without **drops** and **column heads (capitals)**.
- **Drop**: rectangular in plan, length in each direction ≥ **1/3 of panel length**; resists punching and negative moment.
- **Column head**: only the portion within the largest inverted cone/pyramid of **90° vertex angle** is effective.
- Minimum thickness = **125 mm**; span/depth ratio uses longer span; without drops multiply ratio by **0.9**.
- **Column strip** = 0.25 l_2 on each side of column centre line (≤ 0.25 l_1); **middle strip** = remainder.
- Direct design method conditions: ≥ **3 continuous spans** each way, panel long/short ≤ **2**, successive spans differ ≤ 1/3, LL ≤ **3 × DL**.
- Total moment **$M_0 = W l_n/8$**, $l_n \geq 0.65\ l_1$; interior span: **−0.65 M_0** (negative), **+0.35 M_0** (positive).
- Punching shear: critical section at **d/2** from column/drop face; permissible **$k_s \times 0.25 \sqrt{f_{ck}}$**, $k_s = 0.5 + \beta_c \leq 1$.

Staircases (cl 33)

- Supported by beams/walls at top and bottom of flight (parallel to risers): effective span = **c/c of supports**.
- Spanning onto edge of landing slabs that span parallel to risers: span = **going + at each end ½ landing width or 1 m**, whichever smaller.
- Landing spanning in same direction as stair → flight + landing act as **one slab**, span = c/c of supporting beams/walls (going measured horizontally).
- Open-well stairs: load on area common to two spans taken **½ in each direction**.
- Flight embedded ≥ **110 mm** into wall: a 150 mm strip may be deducted from loaded area and effective breadth increased by **75 mm**.
- Stair types by structural action: transversely spanning (cantilever from wall/stringer) vs longitudinally spanning (dog-legged, open-well, folded-plate).

MEMORY TRICK

Span/depth "**7-20-26**" = **C-S-C** (Cantilever-Simple-Continuous). Slab spacing "**3-300 / 5-450**": main 3d or 300, distribution 5d or 450. Min slab steel "**12 for HYSD, 15 for mild**" (per thousand of area).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- A slab is one-way when l_y/l_x is? → **> 2**.
- Basic span/effective depth ratio for continuous beam? → **26**.
- Minimum reinforcement in slab with HYSD bars? → **0.12%** of gross area.
- Maximum diameter of bar in a 150 mm slab? → **18.75 mm** (D/8).
- Max spacing of distribution bars? → **5d or 450 mm**, whichever less.
- Minimum thickness of a flat slab? → **125 mm**.

3.6 Columns & Footings ★★★

- **Column** = compression member with effective length > **3 × least lateral dimension**; **pedestal** = effective length ≤ 3 × least lateral dimension (min steel in pedestal **0.15%**).
- **Short column**: l_{ex}/D and l_{ey}/b both **< 12**; otherwise **slender (long)** (cl 25.1.2).
- Max unsupported length ≤ **60 × least lateral dimension**; cantilever column ≤ $100\ b^2/D$ (cl 25.3).
- **Minimum eccentricity e_{min} = l/500 + D/30, ≥ 20 mm** (cl 25.4).
- Slender column additional moment: **$M_a = (P_u D/2000)(l_e/D)^2$** (cl 39.7).

Effective length of columns (Table 28, Annex E)

End condition	Theoretical	Recommended (IS 456)
Both ends fixed (no sway)	0.5 l	**0.65 l**
One fixed, one hinged	0.7 l	**0.80 l**
Both ends hinged	1.0 l	**1.00 l**
Both fixed, one end free to sway	1.0 l	**1.20 l**
Fixed + partially restrained in rotation, free to sway	—	**1.50 l**
One fixed, other free (flag-pole)	2.0 l	**2.00 l**

KEY FORMULAE – COLUMNS (CL 39)

- Short axially loaded column ($e_{min} \leq 0.05$ D): **$P_u = 0.4 f_{ck} A_c + 0.67 f_y A_{sc}$** ($A_c = A_g - A_{sc}$).
- Helically reinforced column: strength = **1.05 ×** that of tied column, if $V_{helix}/V_{core} \geq$ **$0.36 (A_g/A_k - 1) f_{ck}/f_y$**.
- Pure axial capacity (biaxial check): **$P_{uz} = 0.45 f_{ck} A_c + 0.75 f_y A_{sc}$**.
- Biaxial bending: $(M_{ux}/M_{ux1})^{\alpha_n} + (M_{uy}/M_{uy1})^{\alpha_n} \leq 1$; α_n = **1.0** for $P_u/P_{uz} \leq 0.2$, **2.0** for ≥ 0.8 (linear between).
- WSM axial: $P = \sigma_{cc} A_c + \sigma_{sc} A_{sc}$.

Column detailing (cl 26.5.3)	Value

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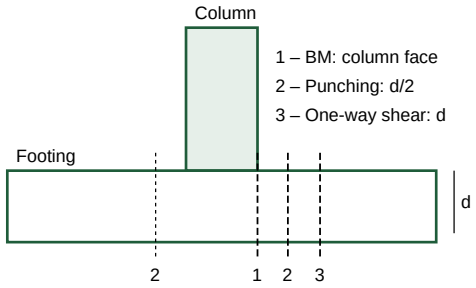
Longitudinal steel	Min **0.8%**, max **6%** of gross area (**4%** recommended max where bars are lapped)
Minimum number of bars	**4** (rectangular); **6** (circular)
Minimum bar diameter	**12 mm**
Spacing of longitudinal bars along periphery	≤ **300 mm**
Lateral tie diameter	≥ $\varphi_{max}/4$ and ≥ **6 mm**
Lateral tie pitch	≤ least of **least lateral dimension, 16** φ_{min} **(smallest longitudinal bar), 300 mm**
Helical pitch	≤ **75 mm** or core dia/6; ≥ **25 mm** or 3 × helix bar dia
Helix diameter	≥ $\varphi_{max}/4$ and ≥ 6 mm
Cover to column bars	≥ **40 mm** (or bar diameter)

Footings (cl 34)

- Thickness at edge ≥ **150 mm** for footings on soil; ≥ **300 mm** above top of piles (cl 34.1.2).
- Plain concrete pedestal/footing: angle of dispersion α with $\tan \alpha \le 0.9\sqrt{(100\, q_0/f_{ck} + 1)}$ (cl 34.1.3).
- **Bending moment** critical section: at **face of column/pedestal/wall** (concrete); **halfway between centre-line and edge of wall** (masonry wall); halfway between face of column and edge of base plate (steel column).
- **One-way (beam) shear**: critical section at distance **d** from face of column.
- **Two-way (punching) shear**: perimeter at **d/2** from column face; permissible $\tau_c' = k_s \times 0.25\sqrt{f_{ck}}$, $k_s = (0.5 + \beta_c) \le 1$, β_c = short/long side of column (cl 31.6.3).
- Development length checked at the same section as BM; also at changes of section.
- Rectangular footing: long-direction steel uniform; short direction – **central band (width = short side of footing)** gets **2/(β + 1)** of total, β = long/short side of footing (cl 34.3.1).
- Bearing at column base: $0.45 f_{ck} \sqrt{(A_1/A_2)}$, with $\sqrt{(A_1/A_2)} \le 2$ (cl 34.4).
- Min steel in footing = as for slab (**0.12%** HYSD); cover **50 mm**.
- Combined footing: used when columns are close or one column is at property line; shaped (trapezoidal/rectangular) so that **CG of loads coincides with centroid of base**. Strap footing – strap beam connects eccentric footing to interior one.



Critical sections in an isolated RC footing (cl 34.2): BM at column face, punching shear perimeter at d/2, one-way shear at d from column face.

MEMORY TRICK

Footing checks "**Face – Half – Full**": BM at the **face**, punching at **half** d, one-way shear at **full** d. Column ties "**16-300-least**": pitch ≤ 16φ, 300 mm, least dimension; tie dia ≥ φ/4 or 6 mm.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- A column is short if l_e/D is less than? → **12**.
- Minimum eccentricity of a column? → **l/500 + D/30, ≥ 20 mm**.
- Minimum and maximum longitudinal steel in columns? → **0.8% and 6%**.
- Minimum number of bars in a circular column? → **6**.
- Critical section for punching shear in footing? → **d/2 from face of column**.
- Minimum depth of footing at edge (on soil)? → **150 mm**.

3.7 Serviceability, Durability & Detailing ★★☆

Serviceability limit (cl 23.2, 35.3)	Value
Final deflection (incl. temperature, creep, shrinkage) – from as-cast level	**span/250**
Deflection after erection of partitions/finishes	**span/350 or 20 mm**, whichever less
Surface crack width – general	**0.3 mm**
Crack width – aggressive environment (severe category)	**0.004 × nominal cover**
Crack width – liquid retaining (IS 3370 Part 2)	**0.2 mm** (0.1 mm where appearance/severe conditions critical)

- Deflection is controlled in practice by **span/depth ratios** (cl 23.2.1); detailed calculation in Annex C (short-term using l_{eff}, plus creep and shrinkage deflection).
- Cracking controlled by **bar spacing** (cl 26.3.3, Table 15): max clear spacing of tension bars (no redistribution) – **Fe 250: 300 mm; Fe 415: 180 mm; Fe 500: 150 mm**.
- Min clear horizontal spacing of bars ≥ **bar diameter** or **(max aggregate size + 5 mm)**, larger; vertical gap between layers ≥ **15 mm, 2/3 aggregate size, bar dia**.

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- **Curtailment** (cl 26.2.3.1): bar extended beyond theoretical cut-off by **d or 12φ**, whichever greater (except at simple support/cantilever end). Bars not to be stopped in tension zone unless shear ≤ **2/3** of permissible or extra stirrups provided.
- Negative steel: ≥ **1/3** of support steel extended beyond point of inflection by **d, 12φ or l_n/16**, greatest (cl 26.2.3.4).
- Durability factors: low w/c, adequate cement content, **cover**, compaction, curing, limits on chlorides & sulphates, crack control.
- Stripping time (cl 11.3.1, OPC): vertical faces **16–24 h**; slab soffits (props left) **3 days**; beam soffits (props left) **7 days**; props to slabs ≤ 4.5 m **7 days**, > 4.5 m **14 days**; props to beams ≤ 6 m **14 days**, > 6 m **21 days**.

Ductile detailing – IS 13920:2016

Item	IS 13920:2016 provision
Applicability	RC structures in **seismic zones III, IV and V**
Concrete grade	Min **M20**; **M25** for buildings taller than **15 m** in zones III–V
Steel	HYSD (IS 1786) with elongation ≥ **14.5%** (Fe 415, Fe 500, Fe 550 "D" grades preferred)
Beam width	≥ **200 mm**; b/D ≥ **0.3**
Beam steel	Min (each face) **0.24 $\sqrt{f_{ck}}/f_y$**; max **2.5%**; bottom steel at joint face ≥ **½ top steel** there
Beam hoops (end zone of 2d)	Spacing ≤ **d/4, 6 φ_{min}, 100 mm**; first hoop ≤ **50 mm** from joint face; elsewhere ≤ **d/2**
Hooks	**135°** hooks with extension **6 φ ≥ 65 mm**
Column minimum dimension	**300 mm** (2016; was 200 mm in 1993)
Column confining zone l_0	≥ larger of **D, l_{clear}/6, 450 mm**; hoop spacing ≤ **¼ min. dimension, 6 φ_{min}, 100 mm**
Strong column – weak beam	**$\Sigma M_c \geq 1.4\ \Sigma M_b$** at each joint
Laps	Not within joints or within 2d of joint face (beams); in columns only in **central half** of clear height; hoops over lap at ≤ 150 mm

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Total deflection limit of beams as per IS 456? → **span/250**.
- Deflection limit after partitions? → **span/350 or 20 mm**, whichever less.
- Permissible surface crack width (normal exposure)? → **0.3 mm**.
- Hook angle in ductile detailing? → **135°**.
- Strong column–weak beam ratio in IS 13920:2016? → **1.4**.
- Minimum props removal time for beams spanning over 6 m? → **21 days**.

3.8 Other RCC & Related Codes ★★☆

Code	Subject
IS 875 (Part 1):1987	**Dead loads** – unit weights of materials
IS 875 (Part 2):1987	**Imposed loads** (live)
IS 875 (Part 3):2015	**Wind loads**
IS 875 (Part 4)	**Snow loads**
IS 875 (Part 5):1987	**Special loads and load combinations**
IS 1893 (Part 1):2016	Earthquake-resistant design – general provisions & buildings
IS 13920:2016	**Ductile design & detailing** of RC structures
IS 4326:2013	Earthquake-resistant construction of (masonry) buildings
IS 3370 (Parts 1–4)	**Liquid-retaining** concrete structures (Part 1 general, Part 2 RCC, Part 3 prestressed, Part 4 design tables)
IS 1343:2012	**Prestressed concrete** (see PSC chapter)
IS 1786:2008	**HYSD/TMT bars** – Fe 415, 415D, 500, 500D, 550, 550D, 600
IS 432 (Part 1)	Mild steel bars (Fe 250)
IS 2502	Bending and fixing of bars
IS 2911	Pile foundations
SP 16	**Design aids** for reinforced concrete to IS 456 (charts/tables)
SP 34	Handbook on **concrete reinforcement and detailing**
SP 24	Explanatory handbook on IS 456 (1978 version)
SP 7	National Building Code (NBC 2016)

Loads – IS 875

- Imposed floor loads (Part 2): residential **2.0 kN/m²**; offices **2.5** (with separate storage) / **4.0** (without); classrooms **3.0**; assembly with fixed seats 4.0, without fixed seats **5.0 kN/m²**.
- Flat/sloping roof (≤ 10°): **1.5 kN/m²** with access, **0.75 kN/m²** without access; for slope > 10°, 0.75 reduced by **0.02 per degree**, min **0.4 kN/m²**.
- Wind (Part 3:2015): **$V_z = V_b\ k_1\ k_2\ k_3\ k_4$** ($k_1$ risk, k_2 terrain/height, k_3 topography, k_4 **importance factor for cyclonic region**); **$p_z = 0.6\ V_z^2$** (N/m²); $p_d = K_d\ K_a\ K_c\ p_z \geq 0.7\ p_z$.
- Basic wind speeds in India: **33, 39, 44, 47, 50, 55 m/s** (3-second gust, 50-year return, 10 m height).

Earthquake – IS 1893 (Part 1):2016

Zone	II	III	IV	V

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Intensity (MSK)	VI (low)	VII (moderate)	VIII (severe)	IX & above (very severe)
Zone factor Z	**0.10**	**0.16**	**0.24**	**0.36**

- Z corresponds to **MCE** (maximum considered earthquake); **Z/2** gives DBE (design basis earthquake).
- **A_h = (Z/2)(I/R)(S_a/g)**; design base shear **V_B = A_h W**.
- Importance factor I: **1.5** (critical/lifeline – hospitals, schools, emergency buildings); **1.2** (business continuity, residential/commercial with > 200 occupants); **1.0** (others).
- Response reduction factor R: **OMRF 3.0**; **SMRF 5.0**; ductile shear wall + SMRF dual system 5.0.
- Natural period: RC MRF (no infill) **T_a = 0.075 $h^{0.75}$**; steel MRF 0.085 $h^{0.75}$; buildings with infill **0.09 h/√d**.
- Seismic weight: imposed load taken **25%** (LL ≤ 3 kN/m²) or **50%** (LL > 3 kN/m²); roof imposed load ignored. Damping **5%** for RC.
- Load combinations: 1.5(DL + IL); **1.2(DL + IL ± EL)**; 1.5(DL ± EL); **0.9 DL ± 1.5 EL**.

CODE UPDATE

BIS notified a revised IS 1893:2025 with a new seismic map that added a highest-hazard **Zone VI** (entire Himalayan arc). It was **withdrawn by gazette notification of 3 March 2026. IS 1893 (Part 1):2016**, with zones **II–V**, is therefore the code in force – answer with 4 zones unless the question says otherwise.

Water tanks (IS 3370) & retaining walls

- IS 3370 (Parts 1 & 2) – 2009 editions, **revised 2021** (second revision) – RCC liquid-retaining: min grade **M30**, max w/c **0.45**, min cement **320 kg/m³** (2009; **350 kg/m³** cementitious in 2021), nominal cover ≥ **45 mm** (at least "severe" exposure of IS 456), crack width **0.2 mm**; design by LSM with crack-width check or by WSM (no cracking).
- Circular tank wall: **hoop tension = γ_w H D/2** per metre height at base (free base); fixed base → part of load by cantilever action.
- **Intze tank** – elevated tank with **conical + spherical bottom**; outward thrust of cone balances inward thrust of bottom dome → economical ring beam for **large capacities**.
- Tank types: resting on ground (flexible or rigid base), underground, elevated; underground tank checked for **uplift** when empty.
- Retaining wall types: **gravity** (up to ~3 m), **cantilever** (up to **~6 m**), **counterfort** (> 6 m; counterforts in tension, spaced ~ H/3 to H/2), buttressed (buttress on front, in compression).
- Cantilever retaining wall: base width ≈ **0.4–0.6 H**; toe ≈ B/3; shear key below base increases sliding resistance (mobilises passive pressure).
- Rankine active coefficient **K_a = (1 − sin φ)/(1 + sin φ)**; passive K_p = 1/K_a; earth pressure resultant at **H/3** from base (dry, horizontal backfill).

Stability check	IS 456:2000 (cl 20)	Common textbook value
Overturning	Restoring moment ≥ **1.2 × M_o(DL) + 1.4 × M_o(IL)**; only **0.9 × DL** counted as restoring	**FOS ≥ 2.0**
Sliding	**FOS ≥ 1.4** (only 0.9 DL counted)	**FOS ≥ 1.5**
Bearing	Max pressure ≤ SBC; no tension at base (resultant within **middle third**)	Same

- Exam tip: if the question says "**as per IS 456**", answer sliding **1.4**; if it asks generally for retaining walls, the textbook values **1.5 (sliding) and 2.0 (overturning)** are expected.

MEMORY TRICK

IS 875 parts "**D-I-W-S-C**" = **D**ead, **I**mposed, **W**ind, **S**now, **C**ombinations (1→5). Zone factors "**10-16-24-36**": each step multiplies by ≈ 1.5.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- IS 875 Part 3 deals with? → **Wind loads**.
- Zone factor for zone V? → **0.36**.
- Response reduction factor for SMRF? → **5**.
- Code for ductile detailing of RC structures? → **IS 13920:2016**.
- SP 34 deals with? → **Reinforcement detailing**.
- FOS against sliding as per IS 456? → **1.4**.

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4. Steel Structures, Design & IS Codes

> **NOTE**
> Expect 5–8 MCQs from steel. Almost all are direct IS 800:2007 values: partial safety factors, bolt hole sizes, pitch/edge limits, fillet weld sizes, slenderness limits, effective length factors, imperfection factors, deflection limits and capacity formulae. Learn the tables in this chapter by heart; derivations are never asked.

4.1 Structural Steel & IS 800:2007 Basics ★★★

- **IS 800:2007** = General Construction in Steel – Code of Practice (3rd revision); adopts **Limit State Method (LSM)** as the main method. WSM is retained in **Section 11** only as an alternative.
- Previous code **IS 800:1984** was based on **Working Stress Method (WSM)**.
- Structural steel specification: **IS 2062:2011** (Hot rolled medium & high tensile structural steel). Grade designation **E250** → E = yield stress grade, 250 = minimum yield stress (MPa).
- E250 sub-qualities **A, BR, B0, C** – differ in impact (Charpy) test requirement; C = killed steel, tested at –20 °C, best weldability.
- Mild steel contains about **0.2–0.25% carbon**; higher carbon → higher strength, lower ductility & weldability.
- Carbon equivalent (CE) governs **weldability**; CE ≤ about 0.42–0.44 for E250.
- Yield stress reduces with plate thickness: E250 → **250 MPa (t < 20 mm)**, 240 MPa (20–40 mm), 230 MPa (> 40 mm).
- Ratio $f_u/f_y \geq$ **1.2** is required for plastic design (ductility).
- Stress–strain curve of mild steel: proportional limit → elastic limit → upper yield → lower yield → yield plateau → **strain hardening** → ultimate → necking → fracture. Strain at onset of strain hardening ≈ **10–12 × yield strain**.

Grade (IS 2062)	f_y (MPa, t < 20 mm)	f_u (MPa)	Min. elongation
E250	**250**	**410**	23%
E275	275	430	22%
E300	300	440	22%
E350	**350**	**490**	22%
E410	410	540	20%
E450	450	570	20%

Physical property of steel (IS 800:2007, cl. 2.2.4.1)	Value
Modulus of elasticity E	**2.0×10^5 MPa** (200 GPa)
Modulus of rigidity G	**0.769×10^5 MPa** (≈ 77 GPa)
Poisson's ratio ν	**0.3** (elastic); 0.5 in plastic range
Unit mass	**7850 kg/m³** (unit weight ≈ 78.5 kN/m³)
Coefficient of thermal expansion α	**12×10^{-6} /°C**

- **Rolled sections** (dimensions IS 808; properties in SP 6(1) Steel Tables): **ISJB** junior beam, **ISLB** light beam, **ISMB** medium beam, **ISWB** wide-flange beam, **ISHB** heavy (column) section, **ISJC/ISLC/ISMC** channels, **ISA** angles (equal & unequal), **ISNT/ISHT** tee bars, ISPL plates, ISFB flats.
- Designation **ISMB 400** → depth = **400 mm**. ISA 100 × 100 × 10 → legs 100 mm, thickness 10 mm.
- **ISHB** is best as column (large r_{yy}); ISMB/ISLB as beams (large Z_{zz}).
- Parallel-flange sections (NPB, WPB) are now also rolled in India (IS 12778).

Partial safety factor for material (Table 5)	γ_m
Resistance governed by **yielding** (γ_{m0})	**1.10**
Resistance of member to **buckling** (γ_{m0})	**1.10**
Resistance governed by **ultimate stress / rupture** (γ_{m1})	**1.25**
Bolts – bearing type (γ_{mb}), shop & field	**1.25**
HSFG bolts – slip resistance at service load (γ_{mf})	**1.10**
HSFG bolts – slip resistance at ultimate load (γ_{mf})	**1.25**
Welds (γ_{mw})	**1.25 shop**; **1.50 field**

Load combination (Table 4, ULS)	DL	IL	WL / EL
DL + IL	**1.5**	**1.5** (leading); 1.05 (accompanying)	–
DL + IL + WL/EL	1.2	1.2 (leading) / 1.05	0.6
DL + IL + WL/EL (wind leading)	1.2	0.53 (accompanying)	1.2
DL + WL/EL	1.5 (**0.9** when DL is stabilising)	–	1.5
Serviceability (DL + IL)	1.0	1.0	–

- **Section classification** (cl. 3.7) depends on width-to-thickness ratio of plate elements in compression, using **$\varepsilon = \sqrt{(250/f_y)}$** (ε = 1 for E250; 0.845 for E350).
- **Class 1 Plastic** – can develop plastic hinge with rotation capacity for **redistribution** of moments (plastic analysis).
- **Class 2 Compact** – can reach M_p but inadequate rotation capacity.

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- **Class 3 Semi-compact** – extreme fibre reaches f_y; local buckling prevents M_p; design on $\mathbf{Z_e}$.
- **Class 4 Slender** – local buckling before yield; uses effective section (cold-formed, IS 801).

Element (Table 2)	Ratio	Plastic	Compact	Semi-compact
Outstand of compression flange – rolled	b/t_f	**9.4ε**	**10.5ε**	**15.7ε**
Outstand of compression flange – welded	b/t_f	8.4ε	9.4ε	13.6ε
Internal element of comp. flange (bending)	b/t_f	29.3ε	33.5ε	42ε
Web, neutral axis at mid-depth	d/t_w	**84ε**	**105ε**	**126ε**
Web under axial compression	d/t_w	–	–	42ε
Angle – compression due to bending (b/t and d/t both)	b/t, d/t	9.4ε	10.5ε	15.7ε
Single angle / double angles (separated) – axial compression	b/t, d/t; (b+d)/t	–	–	15.7ε; 25ε
Circular hollow tube	D/t	$42\varepsilon^2$	$52\varepsilon^2$	$88\varepsilon^2$

- **WSM permissible stresses (IS 800:1984)**: axial tension **0.6 f_y**; bending tension/compression **0.66 f_y**; average shear **0.4 f_y**; maximum shear **0.45 f_y**; bearing **0.75 f_y**; axial compression from Merchant–Rankine formula (max 0.6 f_y).
- WSM: permissible stresses may be increased by **33⅓%** when wind or seismic load is considered (25% for rivets/bolts/welds).
- Factor of safety in WSM ≈ **1.67** on yield (1/0.6).

MEMORY TRICK

"**Zero yields, One ruptures**": γ_{m0} = 1.10 for yielding/buckling, γ_{m1} = 1.25 for rupture. Bolts like rupture (1.25); welds = 1.25 shop, 1.5 field (field work is poorer).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Partial safety factor against yielding as per IS 800:2007? → **1.10**.
- γ_{mw} for field welds? → **1.50**.
- Modulus of rigidity of steel? → **0.769×10^5 N/mm²**.
- Ultimate tensile strength of E250 steel? → **410 MPa**.
- Value of ε for f_y = 250 MPa? → **1.0**.
- Section that cannot develop M_p due to local buckling but reaches f_y at extreme fibre? → **Semi-compact**.

4.2 Bolted Connections ★★★

- **Black bolts** (unfinished, ordinary, IS 1363) – grade **4.6**; bearing-type; hole larger than bolt → used for light/secondary connections.
- **Turned & fitted bolts** (IS 1364) – close tolerance holes; used where slip is not allowed.
- **HSFG bolts** (High Strength Friction Grip, IS 3757; grade **8.8, 10.9**) – load transferred by **friction** between plates due to pre-tension; no slip, good under fatigue/reversal.
- Property class **4.6**: $f_{ub} = 4 \times 100 =$ **400 MPa**; $f_{yb} = 0.6 \times 400 =$ **240 MPa**. Class **8.8**: f_{ub} = **800**, f_{yb} = 640 MPa. Class 10.9: f_{ub} = 1000, f_{yb} = 900 MPa.
- **Net tensile stress area** of threaded bolt $A_{nb} \approx$ **0.78 × gross area** ($\pi d^2/4$).
- Rivets (now obsolete): gross diameter = nominal + **1.5 mm** (d ≤ 25 mm), + **2 mm** (d > 25 mm) – IS 800:1984. Power-driven shop rivets were stronger than field/hand-driven.
- Bolted joints: **lap joint** (single shear, eccentric), **butt joint** with single cover (single shear) or double cover (**double shear**).

Nominal bolt dia d (Table 19)	Standard clearance hole d_0
12, 14 mm	**d + 1 mm** (13, 15)
16, 20, 22, 24 mm	**d + 2 mm** (18, 22, 24, 26)
> 24 mm (30, 36)	**d + 3 mm** (33, 39)

Spacing rule (cl. 10.2)	Limit
Minimum pitch / gauge	**2.5 d** (d = nominal bolt dia)
Maximum pitch – general	**32 t or 300 mm**, whichever less
Maximum pitch – compression member	**12 t or 200 mm**
Maximum pitch – tension member	**16 t or 200 mm**
Maximum gauge (lines adjacent to plate edge)	**100 + 4t or 200 mm**
Minimum edge/end distance – sheared or hand-flame-cut edge	**1.7 d_0** (d_0 = hole dia)
Minimum edge/end distance – rolled, machine-cut, sawn, planed edge	**1.5 d_0**
Maximum edge distance	**12 t ε**; corrosive environment 40 mm + 4t
Tacking fasteners (max spacing)	**32 t or 300 mm**

(t = thickness of thinner outside plate)

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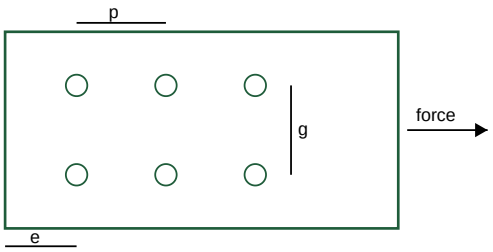

Pitch p (along force), gauge g (across force), end/edge distance e.

- **Failure modes of bolted joint**: (1) shear of bolt, (2) bearing of bolt, (3) bearing (crushing) of plate, (4) tension/rupture of plate at net section, (5) **shear-out/tearing of plate at end** (insufficient end distance), (6) splitting of plate, (7) block shear.
- **Bolt value** = lesser of shear strength and bearing strength. Number of bolts = Load ÷ bolt value.
- **Efficiency of joint** = strength of joint ÷ strength of solid plate × 100.
- **Prying force** – additional tension in bolts of T-stub/end-plate connections due to flexure of the flange.
- Bearing check is **not required for HSFG** (friction-type) at service; slip-resistant joints are designed by friction.

KEY FORMULAE (CL. 10.3, 10.4)

- Shear: $V_{dsb} = V_{nsb}/\gamma_{mb}$; $V_{nsb} = f_{ub}(n_n A_{nb} + n_s A_{sb})/\sqrt{3} \rightarrow V_{dsb} = f_{ub}(n_n A_{nb} + n_s A_{sb})/(\sqrt{3}\,\gamma_{mb})$
  (n_n = shear planes through threads, n_s = through shank)
- Bearing: $V_{dpb} = 2.5\,k_b\,d\,t\,f_u/\gamma_{mb}$; k_b = least of $e/(3d_0)$, $p/(3d_0) - 0.25$, f_{ub}/f_u, **1.0**
- Tension: $T_{db} = T_{nb}/\gamma_{mb}$; $T_{nb} = \mathbf{0.90\,f_{ub}\,A_n} \le f_{yb}\,A_{sb}\,\gamma_{mb}/\gamma_{m0}$
- Combined shear + tension: $(V_{sb}/V_{db})^2 + (T_b/T_{db})^2 \le \mathbf{1.0}$
- Long joint ($l_j > 15d$): $\beta_{lj} = 1.075 - l_j/(200d)$; $\mathbf{0.75 \le \beta_{lj} \le 1.0}$
- Large grip ($l_g > 5d$): $\beta_{lg} = 8d/(3d + l_g) \le \beta_{lj}$; grip $l_g \le 8d$
- Packing plates ($t_{pk} > 6$ mm): $\beta_{pkg} = 1 - 0.0125\,t_{pk}$
- HSFG slip: $V_{dsf} = \mu_f\,n_e\,K_h\,F_0/\gamma_{mf}$; proof load $F_0 = A_{nb} \times \mathbf{0.7}\,f_{ub}$; K_h = 1.0 (clearance hole), 0.85 (oversize/short slot), 0.7 (long slot); $\mu_f \le 0.55$

MEMORY TRICK

Hole: "**1-2-3**" → up to 14 mm add 1, 16–24 add 2, above 24 add 3. Pitch: "**2.5 min; 32/300 general, 16 tension, 12 compression**" – compression gets the tightest spacing (to prevent plate buckling between bolts).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Hole diameter for a 20 mm bolt? → **22 mm**.
- Minimum pitch of bolts? → **2.5 times nominal diameter**.
- Maximum pitch in compression members? → **12t or 200 mm**, whichever is less.
- Edge distance for a sheared edge? → **1.7 × hole diameter**.
- Long-joint reduction applies when joint length exceeds? → **15d**.
- HSFG bolts transfer load by? → **Friction** between the plates.

4.3 Welded Connections ★★★

- Types: **butt (groove) weld**, **fillet weld**, slot weld, plug weld, spot/seam weld. Fillet welds are the most common in structural work.
- Process: arc welding (SMAW – shielded metal arc, SAW – submerged arc, MIG, TIG), gas welding (oxy-acetylene). Electrodes: IS 814.
- Butt weld: **complete penetration** → effective throat = **thickness of thinner part**; strength = parent metal (designed like parent plate).
- Edge preparation for butt welds: square (thin plates, up to ~ 8 mm), single-V, double-V, single-U, double-U, J, bevel. Double-V for thick plates (less weld metal, less distortion).
- Fillet weld: **size s** = leg length (shorter leg for unequal legs); **effective throat t_t = K × s**; K = **0.7** for fusion faces at 60°–90°.
- Fillet welds are permitted only when the angle between fusion faces is **60° to 120°**.
- Effective throat ≥ **3 mm** and generally ≤ 0.7 t (t = thinner plate).
- **Effective length** of fillet weld ≥ **4 × size**; actual length = effective length + **2s** (for end craters). End returns = **2 × size**.
- **Maximum size** of fillet weld: along square edge of plate = **t – 1.5 mm**; along rounded toe of rolled section = **¾ × thickness** of the toe.
- **Minimum lap** in lap joint = **4 × thickness of thinner part or 40 mm**, whichever more.
- **Intermittent fillet welds**: effective length ≥ 4s or 40 mm; clear spacing ≤ **12 t (compression)**, **16 t (tension)**, never > 200 mm.
- Advantages of welding: rigid, airtight/watertight joints, no reduction in area (100% efficiency possible), lighter. Disadvantages: residual stress, distortion, brittle fracture risk, needs skilled labour, inspection costly, fatigue-sensitive.

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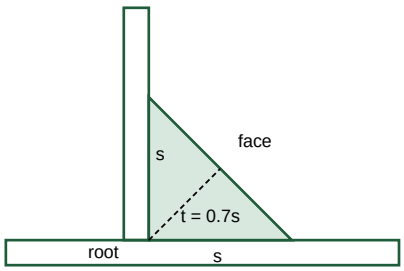

Equal-leg fillet weld: leg (size) s; throat from root perpendicular to face = s cos 45° ≈ 0.7 s.

Thicker part joined (Table 21)	Minimum size of first-run fillet weld
t ≤ 10 mm	**3 mm**
10 < t ≤ 20 mm	**5 mm**
20 < t ≤ 32 mm	**6 mm**
32 < t ≤ 50 mm	**8 mm** first run; **10 mm** minimum size

(Minimum size is also limited to the thinner plate thickness; preheating may be needed for thick plates.)

Angle between fusion faces (Table 22)	K (throat factor)
60°–90°	**0.70**
91°–100°	0.65
101°–106°	0.60
107°–113°	0.55
114°–120°	0.50

KEY FORMULAE (CL. 10.5)

- Design strength of fillet weld: $f_{wd} = f_{wn}/\gamma_{mw} = f_u/(\sqrt{3}\,\gamma_{mw})$ (f_u = smaller of weld/parent metal)
- E250, shop weld: $f_{wd} = 410/(\sqrt{3} \times 1.25) \approx$ **189 MPa**; field: $410/(\sqrt{3} \times 1.5) \approx 158$ MPa
- Weld capacity = $f_{wd} \times t_t \times L_w = f_{wd} \times 0.7s \times L_w$
- Long joint ($L_j > 150\ t_t$): $\beta_{lw} = 1.2 - 0.2L_j/(150\ t_t)$; **$0.6 \le \beta_{lw} \le 1.0$**
- Combined stress in fillet weld: $\sqrt{(f_a^2 + 3q^2)} \le f_u/(\sqrt{3}\,\gamma_{mw})$

Weld defect	Meaning / cause
Undercut	Groove melted into parent metal at toe – excess current/long arc
Porosity	Gas pockets – damp electrodes, contamination
Slag inclusion	Slag trapped between runs – poor cleaning
Incomplete penetration	Weld does not reach root – low current, poor groove
Lack of fusion	Weld metal not fused with parent metal
Cracks (hot/cold)	Most dangerous; high C/H, rapid cooling (lamellar tearing in thick plates)
Overlap	Weld metal flows over the surface without fusion

- **Inspection**: visual; **dye/liquid penetrant** (surface cracks); **magnetic particle** (surface/near-surface, ferrous only); **radiography** (X/γ-ray, internal defects in butt welds); **ultrasonic** (internal, thick sections).
- **Weld symbols** (IS 813): fillet = **triangle**; square butt = two parallel lines; single-V = V; bevel; U; J; plug/slot = rectangle; **flag** at junction = **field (site) weld**; **circle** at junction = **weld all round**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Throat thickness of a 6 mm fillet weld (90° faces)? → **4.2 mm** (0.7 × 6).
- Minimum size of fillet weld for a 16 mm thick plate? → **5 mm**.
- Minimum effective length of a fillet weld? → **4 times the size**.
- Maximum size of fillet weld on square edge of 10 mm plate? → **8.5 mm** (t – 1.5).
- Defect best detected by radiography? → **Internal defects** (porosity, slag, incomplete penetration).
- Symbol for field weld? → **Flag**.

4.4 Tension Members ★★★

- Sections: flats/plates, rods/bars (bracing), single/double angles (trusses), channels, built-up sections, wire ropes/cables.
- Design tensile strength T_d = **least** of (a) gross-section yielding T_{dg}, (b) net-section rupture T_{dn}, (c) block shear T_{db} (Section 6).
- **Net area** (plate, chain bolting): $A_n = (b - n\,d_0)\,t$.
- **Staggered holes** (Cochrane's rule): $A_n = [b - n\,d_0 + \Sigma\, p_{si}^2/(4g_i)]\,t$; p_s = staggered pitch, g = gauge. The **minimum** over all failure paths governs.
- For angles, gauge across the corner = $g_a + g_b - t$.
- **Shear lag** – non-uniform stress when only part of a section (e.g. one leg of an angle) is connected; accounted for by β or α.
- Angles connected by one leg: connected leg fully effective; outstanding leg only partly effective.
- **Lug angle** – short angle connecting outstanding leg to gusset to reduce connection length (reduce shear lag). Lug-to-gusset connection: **20% in excess** of force in outstanding leg (angle members), 10% (channels); lug-to-member connection: **40% in excess** (angles), 20% (channels). Minimum **2 bolts**.
- Tension splices designed for the full design strength of member (or actual force).

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KEY FORMULAE (SECTION 6)

- Yielding of gross section: $T_{dg} = A_g f_y/\gamma_{m0}$
- Rupture of plate: $T_{dn} = 0.9\, A_n f_u/\gamma_{m1}$
- Rupture of angle: $T_{dn} = 0.9\, A_{nc} f_u/\gamma_{m1} + \beta\, A_{go} f_y/\gamma_{m0}$
- $\beta = 1.4 - 0.076\,(w/t)(f_y/f_u)(b_s/L_c)$; $0.7 \le \beta \le f_u\gamma_{m0}/(f_y\gamma_{m1})$
- Preliminary: $T_{dn} = \alpha\, A_n f_u/\gamma_{m1}$; α = **0.6** (1–2 bolts), **0.7** (3 bolts), **0.8** (≥ 4 bolts or welded)
- Block shear (smaller of): $T_{db1} = A_{vg}f_y/(\sqrt{3}\gamma_{m0}) + 0.9A_{tn}f_u/\gamma_{m1}$; $T_{db2} = 0.9A_{vn}f_u/(\sqrt{3}\gamma_{m1}) + A_{tg}f_y/\gamma_{m0}$

Member (IS 800:2007 Table 3)	Max. slenderness ratio KL/r
Member carrying compressive load from dead & imposed loads	**180**
Tension member with stress reversal due to loads other than wind/EQ	**180**
Member in compression only due to wind/EQ (deformation not affecting stress)	**250**
Compression flange of beam against lateral torsional buckling	**300**
Tie in roof truss / bracing, reversal only from wind/EQ	**350**
Member always in tension (other than pre-tensioned)	**400**

MEMORY TRICK

Slenderness ladder "**180 – 250 – 300 – 350 – 400**": Gravity strut 180 → wind strut 250 → beam flange 300 → wind-reversed tie 350 → pure tie 400. Lug angle "**20-40 angle, 10-20 channel**".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Net area allowance for staggered holes adds? → **$p^2/4g$** per inclined segment.
- Maximum slenderness ratio for a member always in tension? → **400**.
- Design strength due to yielding of gross section? → **$A_g f_y/1.10$**.
- Lug angles are used to? → **Reduce length of end connection** (and shear lag).
- Failure where a block tears out along shear and tension planes? → **Block shear**.

4.5 Compression Members ★★★

- Names: **column/stanchion** (building, vertical), **strut** (truss/any compression member), **boom/principal rafter** (top chord of truss), **post**.
- Short column fails by crushing (yield); long column by **buckling** (Euler $P_{cr} = \pi^2 EI/(KL)^2$); intermediate by inelastic buckling.
- IS 800:2007 uses **Perry–Robertson** type multiple column curves (a, b, c, d) based on ECCS; IS 800:1984 used **Merchant–Rankine** formula.
- Imperfections causing lower strength: initial crookedness, residual stresses, eccentricity of load.
- Most efficient section for column: **circular/square tube** (equal r in all directions); among rolled: ISHB.
- Max. KL/r for compression members: **180** (DL + IL); 250 (wind/EQ only).

End conditions (Table 11)	Effective length KL
Both ends fixed (translation & rotation restrained)	**0.65 L**
One end fixed, other hinged (translation restrained both)	**0.80 L**
Both ends hinged	**1.0 L**
Both ends rotation restrained, one end free to sway	**1.2 L**
One end fixed, other free (cantilever/flagpole)	**2.0 L**
One end hinged, other rotation restrained but free to sway	**2.0 L**

(Theoretical values are 0.5L, 0.7L, 1.0L, 1.0L, 2.0L, 2.0L; IS 800 gives higher practical values for fixed ends.)

Buckling class	Imperfection factor α	Typical sections (Table 10)
a	**0.21**	Hot-rolled hollow sections; rolled I with $h/b_f > 1.2$, $t_f \le 40$ mm – about z-z
b	**0.34**	Rolled I ($h/b_f > 1.2$, $t_f \le 40$) about y-y; cold-formed hollow; welded I ($t_f \le 40$) about z-z; welded box (generally)
c	**0.49**	**Channels, angles, T-sections, solid sections** (any axis); **built-up members**; welded I ($t_f \le 40$) about y-y; rolled I with $h/b_f \le 1.2$ about y-y
d	**0.76**	Very thick flanges: rolled I with $h/b_f \le 1.2$, $t_f > 100$ mm; welded I with $t_f >$ 40 mm about y-y

KEY FORMULAE (CL. 7.1.2)

- Design compressive strength: $P_d = A_e f_{cd}$
- $f_{cd} = (f_y/\gamma_{m0}) / [\varphi + \sqrt{(\varphi^2 - \lambda^2)}] \le f_y/\gamma_{m0}$ ($= \chi\, f_y/\gamma_{m0}$)
- $\varphi = 0.5\,[1 + \alpha(\lambda - 0.2) + \lambda^2]$
- Non-dimensional slenderness $\lambda = \sqrt{(f_y/f_{cc})}$; Euler stress $f_{cc} = \pi^2E/(KL/r)^2$
- For $\lambda \le 0.2$, no buckling reduction ($f_{cd} = f_y/\gamma_{m0}$)
- Old WSM (IS 800:1984): Merchant–Rankine $\sigma_{ac} = 0.6\, f_{cc}f_y/[f_{cc}^{\,n} + f_y^{\,n}]^{1/n}$, n = 1.4

- **Built-up columns**: two channels (back-to-back or toe-to-toe) or I-sections connected by **lacing** or **battens** so that $r_{yy} \ge r_{zz}$ (more economical).
- **Lacing** (cl. 7.6): inclination **40°–70°** to member axis; transverse shear for design = **2.5% of axial force**;

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slenderness of lacing bar ≤ **145**; min. width of bar = **3 × nominal bolt dia**; thickness ≥ **1/40** (single lacing) or **1/60** (double lacing) of effective length of bar.

- Effective length of lacing bar: single lacing bolted = L (between inner fasteners); double lacing bolted = 0.7 L; welded = 0.7 L.
- Spacing of lacing such that slenderness of each component between connections ≤ **50** or **0.7 × max. slenderness of the whole member**, whichever less.
- Effective slenderness of laced column increased by **5%** (1.05 KL/r) to allow for shear deformation.
- Lacing system must be uniform throughout length; **tie plates** at ends and where lacing is interrupted. Single lacing on opposite faces should be shadows of each other.
- **Battens** (cl. 7.7): used for axially loaded columns; ≥ 2 main components; effective slenderness increased by **10%** (1.1 KL/r); transverse shear V_t = **2.5%** of axial force; component slenderness between battens ≤ **50** or 0.7 × whole member slenderness.
- Batten depth: end battens ≥ distance between centroids of main members; intermediate battens ≥ ¾ of that; and not less than twice the width of one member. Thickness ≥ **1/50** of distance between innermost connecting lines. Battens are placed opposite each other on both faces.
- Battened columns are weaker against shear than laced; lacing preferred for eccentric loads.
- **Column bases**: **slab base** (thick plate, light loads; column end machined for direct bearing) and **gusseted base** (gusset plates/angles + thinner base plate, heavy loads/moments).
- Bearing strength of concrete under base plate per IS 800:2007 = **0.6 f_{ck}** (IS 456 uses 0.45 f_{ck}).
- Area of base plate = factored load ÷ bearing strength of concrete.

SLAB BASE THICKNESS (CL. 7.4.3.1)

- $t_s = \sqrt{[2.5\, w\, (a^2 - 0.3\, b^2)\, \gamma_{m0}/f_y]} > t_f$ (flange thickness of column)
- w = uniform bearing pressure from below; a, b = larger and smaller projections of base plate beyond the column

MEMORY TRICK

Buckling classes "**a-b-c-d = 0.21, 0.34, 0.49, 0.76**" (each roughly +0.13 to +0.27). "**Lacing 5, Batten 10**" – % increase in slenderness. Lacing angle "**40 to 70**", lacing bar slenderness "**145**".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Effective length of column fixed at both ends as per IS 800? → **0.65 L**.
- Imperfection factor for buckling class c? → **0.49**.
- Buckling class for single angle sections? → **Class c**.
- Angle of lacing bars with the axis of member? → **40° to 70°**.
- Lacing system is designed for transverse shear of? → **2.5% of axial load**.
- Bearing strength of concrete under a steel base plate (IS 800)? → **0.6 f_{ck}**.

4.6 Beams & Plate Girders ★★★

- **Laterally supported beam** – compression flange restrained (e.g. by slab), so no lateral torsional buckling (LTB); strength = full section capacity.
- **Laterally unsupported beam** – compression flange free to buckle sideways and twist → **LTB**; design bending stress $f_{bd} = \chi_{LT}\, f_y/\gamma_{m0}$.
- Imperfection factor for LTB: α_{LT} = **0.21 rolled**, **0.49 welded** sections.
- LTB depends on: unbraced length, I_y, torsion constant I_t, warping constant I_w, load position (top-flange load is destabilising), end restraint.
- LTB need not be checked for bending about the **minor axis**, or when $\lambda_{LT} \le 0.4$.
- **Shear centre** – point through which load must pass to avoid twisting; for channel it lies **outside the web** (away from flanges); for I-section at centroid; for angle and T at the intersection of legs/flange-web.
- **Web buckling** (as a strut under concentrated load, effective length 0.7d with 45° dispersion to NA) and **web crippling** (local yielding at web–flange junction, dispersion 1:2.5 through flange) must be checked at supports and point loads; else provide **bearing stiffeners**.
- Shear buckling of web need not be checked if $d/t_w \le$ **67ε** (unstiffened web).

KEY FORMULAE (SECTION 8)

- Laterally supported, low shear ($V \le 0.6V_d$): $\mathbf{M_d = \beta_b\, Z_p\, f_y/\gamma_{m0}}$; β_b = **1.0** (plastic, compact), $\mathbf{Z_e/Z_p}$ (semi-compact)
- Limit (to avoid irreversible deformation at service): $M_d \le$ $\mathbf{1.2\, Z_e f_y/\gamma_{m0}}$ (simply supported); $\le$ $\mathbf{1.5\, Z_e f_y/\gamma_{m0}}$ (cantilever)
- Shear: $\mathbf{V_d = A_v\, f_{yw}/(\sqrt{3}\, \gamma_{m0})}$; A_v = h t_w (rolled I, major axis), d t_w (welded I), $2b_f t_f$ (I, minor axis)
- High shear ($\mathbf{V > 0.6\, V_d}$): $M_{dv} = M_d - \beta(M_d - M_{fd})$, $\beta = (2V/V_d - 1)^2$; M_{fd} = plastic moment of flanges alone
- Unsupported: $M_d = \beta_b\, Z_p\, f_{bd}$; $\lambda_{LT} = \sqrt{(\beta_b Z_p f_y/M_{cr})}$
- Web crippling: $F_w = (b_1 + n_2)\, t_w\, f_{yw}/\gamma_{m0}$, n_2 = 2.5 × (flange thickness + root radius)

Building / member (Table 6)	Load	Deflection limit

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Other buildings – floor/roof, elements not susceptible to cracking	Live	**Span/300**
Other buildings – floor/roof, brittle finishes (susceptible to cracking)	Live	**Span/360**
Other buildings – cantilever	Live	Span/150 ; Span/180 (brittle)
Industrial – purlins & girts	Live/wind	**Span/150** (elastic cladding); Span/180 (brittle)
Industrial – simple span members	Live	Span/240 (elastic); Span/300 (brittle)
Gantry – manually operated crane	Crane	**Span/500**
Gantry – EOT crane up to 50 t	Crane	**Span/750**
Gantry – EOT crane over 50 t	Crane	**Span/1000**

- **Plate girder** – built-up I-beam (web plate + flange plates/angles, riveted/bolted or welded) for large spans and heavy loads beyond rolled sections (spans ~ 20–40 m in bridges).
- Components: **web plate** (resists shear), **flanges** (resist bending), **cover plates** (curtailed where BM reduces), **bearing stiffeners** (at supports and point loads; designed as columns, effective length **0.7 × length**), **intermediate (transverse) stiffeners** (prevent shear buckling), **longitudinal stiffeners** (prevent bending buckling of web; first at **0.2d** from compression flange, second at **neutral axis**), web & flange splices.
- **Economic depth**: $d = (M\ k/f_y)^{1/3}$, $k = d/t_w$; at economic depth, weight of web ≈ weight of flanges. Rough depth ≈ **span/10 to span/12** (buildings).
- **Tension field action** (post-buckling strength of web, cl. 8.4.2.2) can be used in stiffened webs to increase shear capacity – needs end panels anchored.
- **Web thickness limits** (serviceability, cl. 8.6.1.1): no stiffeners $d/t_w \le$ **200ε**; transverse stiffeners only – up to about 270ε depending on spacing; with one longitudinal stiffener at 0.2d ≤ **250ε**; with second longitudinal stiffener at NA ≤ **400ε**.
- Compression-flange buckling requirement: $d/t_w \le$ **$345\varepsilon_f^2$** (stiffener spacing c ≥ 1.5d).
- Stiffener outstand ≤ **$20\ t_q\ \varepsilon$**; if it exceeds **$14\ t_q\ \varepsilon$**, only $14\ t_q\ \varepsilon$ is taken as effective.
- Spacing of intermediate stiffeners generally between 0.33d and 3d (c/d ≤ 3, beyond which web treated as unstiffened).

MEMORY TRICK

Deflection "**300 – 360**" for ordinary buildings; gantry "**500 – 750 – 1000**" (hand → EOT ≤ 50 t → EOT > 50 t). Web "**67 – 200 – 250 – 400**": no shear-buckling check → no stiffener → one longitudinal → two longitudinal.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- High shear condition in IS 800:2007? → **$V > 0.6\ V_d$**.
- β_b for a semi-compact section? → **Z_e/Z_p**.
- Deflection limit for gantry girder with EOT crane of 30 t? → **Span/750**.
- Bearing stiffeners are designed as? → **Columns** (effective length 0.7 L).
- Shear centre of a channel section lies? → **Outside the web**, on the axis of symmetry.
- First longitudinal stiffener in a plate girder is placed at? → **0.2d from compression flange**.

4.7 Roof Trusses, Industrial Buildings & Others ★★☆

Truss type	Key feature
Pratt	Diagonals in **tension**, verticals in compression under gravity load – suited to steel
Howe	Diagonals in **compression**, verticals in tension – suited to timber (with steel tie rods)
Fink (French)	Short compression members, economical for pitched roofs of medium–large span; compound Fink for larger spans
Fan	Modified Fink; rafter divided for purlins at panel points
North-light (saw-tooth)	Factories/workshops; steep glazed face towards **north** (diffused light, no glare)
Warren	Diagonals alternately in tension & compression, no verticals – bridges, flat roofs
King post / Queen post	Short spans (timber roofs)
Quadrangular / Bowstring	Large spans, curved top chord

- **Pitch** of truss = rise ÷ span; commonly **¼ to ⅙** of span for sheet roofs.
- **Economic spacing of trusses**: cost of trusses = **2 × cost of purlins + cost of roof covering** (t = 2p + r). Usual spacing ≈ **1/3 to 1/5 of span** (about 3–4.5 m for light roofs).
- Purlins placed at **panel points** to avoid bending in rafter; if not, rafter is designed for combined bending + compression.
- **Angle purlins** (IS 800:1984 rules, still used in practice): roof slope ≤ **30°**; BM = **WL/10**; depth of leg perpendicular to roof ≥ **L/45**; width of leg parallel to roof ≥ **L/60** (L = purlin span). Purlins are designed as continuous beams; channel/Z/cold-formed purlins are common now.
- Purlin subjected to **unsymmetrical (biaxial) bending** because load acts vertically while section axes are inclined; sag rods reduce minor-axis span.
- Imposed load on roofs (IS 875 Part 2:1987): access roof 1.5 kN/m²; no access (slope ≤ 10°) **0.75 kN/m²**, reduced by **0.02 kN/m² per degree** above 10°, minimum **0.4 kN/m²**.

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- **Wind load** (IS 875 Part 3:2015): $V_z = V_b\, k_1 k_2 k_3 k_4$ (k_1 risk/probability, k_2 terrain–height, k_3 topography, k_4 importance for cyclonic region); $p_z = \mathbf{0.6\, V_z^2}$ (N/m²); $p_d = K_d K_a K_c p_z \geq \mathbf{0.7\, p_z}$.
- Basic wind speeds in India: **33 to 55 m/s** (6 zones); based on 3-second gust, 50-year return period, 10 m height.
- Wind on roof: $F = (C_{pe} - C_{pi})\, A\, p_d$; $C_{pi} = \pm 0.2$ (low permeability), ±0.5 (medium), ±0.7 (large openings). **Suction (uplift)** on leeward/low-slope roofs may cause **stress reversal** in truss members – check with **0.9 DL + 1.5 WL**.
- Bracing: **rafter (roof) bracing**, **vertical (column) bracing**, eaves strut – transfer longitudinal wind/crane forces.

Gantry girder – crane load allowance (IS 800:2007 / IS 875-2)	Value
Vertical impact – EOT crane	**25%** of max static wheel load
Vertical impact – hand-operated crane	**10%**
Lateral (surge) – EOT crane	**10%** of (crab + lifted load)
Lateral – hand-operated crane	5% of (crab + lifted load)
Longitudinal (drag/braking) – EOT & hand	**5%** of static wheel loads

- Gantry girder section: **I-section with channel** on top flange (resists lateral surge), or plate girder for heavy cranes; designed as **laterally unsupported** beam under biaxial bending.
- Max BM under moving wheel loads: occurs under a wheel when that wheel and the CG of loads are **equidistant from mid-span**.
- **Cold-formed light gauge sections**: IS 801:1975 (design), IS 811 (sections); thickness about 1–8 mm; formed at room temperature (cold rolling/press braking) – strength increases due to strain hardening; local buckling governs → **effective width** concept; used for purlins, girts, sheeting, light frames.
- **Corrosion protection**: surface prep (sand/shot blasting), primer (red oxide / zinc chromate / zinc-rich), finish paint; **hot-dip galvanising** (zinc – sacrificial protection); **weathering steel** (IS 11587, Cu-alloyed); avoid water traps. Durability – Section 15 of IS 800:2007.
- **Fire**: steel is non-combustible but loses strength rapidly; at about **550 °C** yield strength falls to ≈ 60% (critical temperature for loaded members). Protection – concrete encasement, intumescent paint, sprayed vermiculite/gypsum boards. Fire resistance – Section 16 of IS 800:2007.
- **Steel tanks**: pressed steel tanks **IS 804** (panels **1.22 m × 1.22 m**); gravity water tanks IS 805. Cylindrical tanks with ring girder at top; hoop tension governs shell design.
- **Steel chimneys/stacks**: **IS 6533** (Part 1 mechanical, Part 2 structural); self-supporting or guyed; check wind, oscillation (vortex shedding), corrosion allowance.
- **Transmission towers**: IS 802; **pre-engineered buildings (PEB)** use tapered built-up sections + cold-formed purlins.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Economic spacing of roof trusses is when? → **Cost of truss = 2 × cost of purlins + cost of roof covering**.
- In a Pratt truss under gravity loads, diagonals are in? → **Tension**.
- Vertical impact allowance for EOT crane gantry girders? → **25%**.
- Lateral surge of EOT crane? → **10% of weight of crab + lifted load**.
- Design wind pressure p_z in terms of V_z? → $\mathbf{0.6\, V_z^2}$.
- Code for cold-formed light gauge steel design? → **IS 801**.

4.8 Plastic Analysis in Steel ★★☆

- Assumes steel is **ideally elastic–perfectly plastic**; at full plasticity the section forms a **plastic hinge** (rotates at constant M_p).
- **Plastic moment** $M_p = Z_p f_y$; **plastic modulus** $Z_p = (A/2)(y_1 + y_2)$ – first moment of areas above and below the **equal-area axis** (plastic neutral axis divides area equally).
- **Shape factor** $S = M_p/M_y = \mathbf{Z_p/Z_e}$ – depends only on geometry of section, always > 1.
- **Load factor** = collapse load ÷ working load; = shape factor × factor of safety (WSM). IS 800:1984 plastic design load factor = **1.7** (DL + LL), 1.3 with wind/EQ.
- Number of plastic hinges for complete collapse = **r + 1** (r = degree of static indeterminacy); fewer hinges → partial collapse.
- Theorems: **static (lower bound)** → load ≤ collapse load (safe); **kinematic (upper bound)** → load ≥ collapse load (unsafe); **uniqueness** → both satisfied gives true collapse load.
- Only **plastic (Class 1)** sections may be used where plastic hinges form in plastic analysis.
- Collapse loads of standard beams (simply supported $4M_p/L$; fixed with central load $8M_p/L$; fixed with UDL $16M_p/L$; propped cantilever with UDL $11.66M_p/L$) – see **Chapter 2**.

Section	Z_p	Shape factor
Rectangle (b × d)	$bd^2/4$	**1.5**
Solid circle (dia d)	$d^3/6$	**1.70** (16/3π)
Thin circular tube	–	**1.27** (4/π)
Diamond (square on diagonal)	–	**2.0**
Triangle (base horizontal)	–	**2.34**
I-section (rolled, major axis)	–	**1.12–1.15** (≈ 1.14)

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I-section (minor axis)	–	≈ 1.5–1.6

MEMORY TRICK

Shape factor ascending: "**I (1.14) < Tube (1.27) < Rectangle (1.5) < Circle (1.7) < Diamond (2.0) < Triangle (2.34)**" – the more material near the neutral axis, the higher the shape factor.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Shape factor of a rectangular section? → **1.5**.
- Shape factor of a solid circular section? → **1.7**.
- Plastic neutral axis divides the section into? → **Two equal areas**.
- Number of plastic hinges for collapse of a fixed beam (r = 2)? → **3**.
- Kinematic (mechanism) method gives? → **Upper bound** of collapse load.

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5. Concrete Technology & Prestressed Concrete

> **NOTE**
>
> Concrete Technology usually gives **5–8 of the 60 questions** in Civil PSU/JE/AE papers. Most are one-line facts: Bogue compounds and their roles, IS limits of cement tests, aggregate test limits, workability test ranges, IS 10262:2019 target strength, IS 456 sampling and acceptance, creep coefficient, and prestress losses. Learn the numbers in the tables. For a warehousing body like CWC, also note RMC, curing, NDT of existing structures and durability.

5.1 Cement – Composition & Types ★★★

- **Portland cement** was patented by **Joseph Aspdin (1824)**, England. It is named after Portland stone, which it resembles when set. I.C. Johnson (1845) first burnt the mix to clinkering temperature.
- **Raw materials**: a **calcareous** one (limestone, chalk, marl), which supplies CaO, and an **argillaceous** one (clay, shale), which supplies SiO_2, Al_2O_3 and Fe_2O_3. They are mixed in about **3:1** proportion.
- **Wet process**: raw materials ground into a **slurry (35–50% water)**; suits soft chalk; more fuel, longer kiln; now obsolete. **Dry process**: ground dry into raw meal; **less fuel**, shorter kiln; with pre-heater/pre-calciner it is **now used in almost all Indian plants**.
- **Rotary kiln**: a steel shell lined with refractory, sloping about **1 in 25 to 1 in 30** and rotating at **1–2 rpm**. Its zones are drying (~100–450 °C), **calcination** ($CaCO_3 \rightarrow CaO + CO_2$, ~800–1000 °C) and the **burning/clinkering zone at 1400–1500 °C**, where the compounds form as **clinker** (3–20 mm nodules).
- Clinker is cooled and ground with **gypsum ($CaSO_4 \cdot 2H_2O$) ≈ 3–5%**. Gypsum is a **retarder**: it reacts with C_3A to form ettringite and so prevents **flash set**.

Oxide	Typical % in OPC	Role / remark
Lime, CaO	**60–67**	Main constituent; strength. Excess free lime → **unsoundness**
Silica, SiO_2	**17–25**	Forms C_3S and C_2S; strength
Alumina, Al_2O_3	**3–8**	Quick setting; acts as a flux, lowering the clinkering temperature
Iron oxide, Fe_2O_3	0.5–6	**Grey colour**; flux
Magnesia, MgO	0.1–4	Excess → unsoundness. IS 269 limit **≤ 6%**
Sulphur trioxide, SO_3	1–3	From gypsum; excess → unsoundness
Alkalis (Na_2O, K_2O)	0.4–1.3	Efflorescence; **alkali-aggregate reaction**

- **Lime Saturation Factor (LSF)** = $(CaO - 0.7\ SO_3) / (2.8\ SiO_2 + 1.2\ Al_2O_3 + 0.65\ Fe_2O_3)$. For OPC it lies between **0.80 and 1.02** (0.66–1.02 for 33 grade, IS 269:2015). Alumina–iron ratio (A/F) **≥ 0.66**. Chloride ≤ **0.1%** (≤ 0.05% for prestressed work).

Bogue compound	Formula / name	% in OPC	Heat of hydration	Role
C_3S	$3CaO \cdot SiO_2$, tricalcium silicate (alite)	**40–50** (~45)	~500 J/g (120 cal/g)	**Early strength (first 7 days)**; hardens fast; more $Ca(OH)_2$
C_2S	$2CaO \cdot SiO_2$, dicalcium silicate (belite)	**20–30** (~25)	**Lowest**, ~260 J/g (62 cal/g)	**Later strength (after 28 days)**; better chemical resistance
C_3A	$3CaO \cdot Al_2O_3$, tricalcium aluminate	**5–11**	**Highest**, ~865 J/g (207 cal/g)	**Reacts first**; flash set; little strength; **poor sulphate resistance**
C_4AF	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$, tetracalcium aluminoferrite (celite)	**8–14**	~420 J/g (100 cal/g)	Least strength contribution; colour

- The order of rate of hydration and of heat is **$C_3A > C_3S > C_4AF > C_2S$**.
- Hydration of the silicates gives **C-S-H gel (tobermorite gel)**, the main strength-giving product, plus **$Ca(OH)_2$**, which keeps pH ≈ 12.5–13 and protects steel but is weak and leachable. C_3S gives about **61% C-S-H and 39% CH**. C_2S gives about **82% C-S-H and 18% CH**, so C_2S is more durable.
- Water needed: chemically combined (bound) water ≈ **23%** of cement mass, and gel water ≈ **15%**. Complete hydration therefore needs w/c ≈ **0.38**; this is often quoted as 0.38–0.42.
- Specific gravity: OPC = **3.15**, PPC ≈ **2.9**. Bulk density = **1440 kg/m³**. One bag of **50 kg = 0.0347 m³ (≈ 35 L)**.
- Cement loses strength in storage, even in good conditions: about **20% after 3 months, 30% after 6 months and 40% after 12 months**. Stack bags **≤ 10 high**, 150–200 mm above the floor and about 300–450 mm clear of walls (texts vary), and issue on a **first-in first-out** basis.

Cement type	IS code	Key feature / use
OPC 33, 43, 53 grade (and 43-S, 53-S)	**IS 269:2015**	Grade = minimum 28-day strength in MPa. One code now covers all OPC grades.
Sleeper cement	**IRS-T40** (53-S in IS 269)	Railway **PSC sleepers**; high C_3S; fineness ≥ 370 m^2/kg

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Portland Pozzolana Cement (PPC)	**IS 1489 (Part 1):2015** fly ash; Part 2 calcined clay	**Fly ash 15–35%**; low heat, better durability, slow early strength; mass concrete, marine works, hydraulic structures
Portland Slag Cement (PSC)	**IS 455:2015**	**GGBS 25–70%**; sulphate/sea-water resistance, low heat; marine and sewage works
Rapid Hardening (RHC)	IS 8041	More C_3S, finer grinding (≥ **325 m²/kg**). **3-day strength ≈ 7-day strength of OPC**. Early form removal, road repairs. Its setting time is the same as OPC.
Low Heat	IS 12600	Low C_3S and C_3A, high C_2S. Heat ≤ **272 kJ/kg (65 cal/g) at 7 days** and ≤ 314 kJ/kg (75 cal/g) at 28 days. Initial set ≥ **60 min**. Used in **mass concrete (dams)**.
Sulphate Resisting (SRC)	IS 12330	**C_3A ≤ 5%** and $2C_3A + C_4AF$ ≤ 25%. For sulphate soils, sewers and marine work.
White cement	IS 8042	Very low Fe_2O_3 (and MnO). Fired with oil or gas, not coal. Used for finishes and terrazzo.
Hydrophobic	IS 8043	Grains carry a water-repellent film (oleic or stearic acid). For long storage in **humid areas**.
High Alumina (HAC)	IS 6452	Bauxite + limestone, Al_2O_3 ≈ 40%. **Very high 1-day strength**, but it sets normally. Refractory and resists sulphates. **Conversion** causes loss of strength, so it is not used structurally.
Quick setting	—	Less gypsum, plus aluminium sulphate. **Initial set ≈ 5 min, final ≈ 30 min**. For **under-water / flowing water** work.
Supersulphated	IS 6909	Slag 80–85% + $CaSO_4$ 10–15% + ~5% clinker. Highly sulphate resistant.

Minimum compressive strength (MPa)	3 days (72 h)	7 days (168 h)	28 days (672 h)
OPC 33	16	22	**33** (max 48)
OPC 43	23	33	**43** (max 58)
OPC 53	27	37	**53**
PPC / PSC	16	22	**33**

CODE UPDATE

IS 269:2015 merged the old IS 269 (33 grade), IS 8112 (43 grade) and IS 12269 (53 grade) into one code for OPC. It also brought in the 43-S and 53-S sleeper grades and an upper limit on 28-day strength for 33 and 43 grade. PPC (IS 1489) and PSC (IS 455) were also revised in 2015.

MEMORY TRICK

"**3S = Speedy, 2S = Slow, 3A = Angry (flash, most heat), 4AF = Almost Futile.**" For heat, think "A-S-F-2": $C_3A > C_3S > C_4AF > C_2S$.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Which compound gives early strength? → **C_3S**.
- Which compound liberates the maximum heat of hydration? → **C_3A**.
- Gypsum is added to cement to? → **Retard setting (prevent flash set)**.
- Cement used for dam construction? → **Low heat cement**.
- Maximum C_3A in sulphate resisting cement? → **5%**.
- Specific gravity of OPC? → **3.15**.

5.2 Tests on Cement ★★★

- Laboratory tests on cement are covered by **IS 4031 (Parts 1–15)**. Standard sand is **Ennore sand, IS 650**. Tests are done at **27 ± 2 °C** and RH ≥ 65% (moist room ≥ 90%).
- **Fineness** (IS 4031 Part 1/Part 2). Finer cement gives faster hydration, more early strength, more heat, more shrinkage and more bleeding resistance.
  - Sieve test: residue on the **90 µm sieve ≤ 10%** for OPC (older criterion).
  - **Blaine air-permeability** method (specific surface): OPC ≥ **225 m²/kg**, PPC ≥ **300 m²/kg**, RHC ≥ 325 m²/kg, low heat ≥ 320 m²/kg. Other methods are the Wagner turbidimeter and Lea & Nurse.
- **Standard (normal) consistency** (Vicat apparatus, IS 4031 Part 4). This is the water content at which the **Vicat plunger (10 mm dia, 50 mm long)** penetrates to **5–7 mm from the bottom** of the mould (33–35 mm from the top). It is usually **26–33%** and is written **P**. Mould height **40 mm**. Gauging time is **3–5 min**.
- **Initial setting time** (IS 4031 Part 5): use paste with **0.85 P** water and the **1 mm square needle**. It is the time at which the needle **fails to pierce beyond 5 ± 0.5 mm from the bottom**. For OPC it must be **≥ 30 min**.
- **Final setting time**: the needle with the **5 mm dia annular collar**. It is the time at which the needle makes an impression but the **collar does not**. For OPC it must be **≤ 600 min (10 h)**.
- **Soundness** means no undue expansion after setting. Unsoundness is caused by **free lime, MgO and excess SO_3**.

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- **Le Chatelier** test (IS 4031 Part 3): split brass cylinder 30 mm dia × 30 mm high with indicators; paste with **0.78 P** water; boil for **3 h**. Expansion **≤ 10 mm**. It detects **free lime only**.
- **Autoclave** test (25 × 25 × 250 mm bar at **2.1 MPa steam for 3 h**): expansion **≤ 0.8%**. It detects **both free lime and MgO**, and is required when MgO > 3%.

- **Compressive strength** (IS 4031 Part 6): **1:3 cement : standard sand** mortar (200 g cement + 600 g sand). Water = **(P/4 + 3.0)%** of the combined mass of cement and sand. Cubes are **70.6 mm (face area 50 cm²)**, compacted on a vibration machine at **12000 ± 400 vibrations/min for 2 min**. They are tested at **3, 7 and 28 days** (72 ± 1 h, 168 ± 2 h, 672 ± 4 h).
- **Heat of hydration** (IS 4031 Part 9) is measured with a **calorimeter**. It matters for mass concrete.
- **Specific gravity** is found with the **Le Chatelier flask using kerosene**, not water, because cement reacts with water.

Test	Apparatus	Water used	IS limit (OPC)
Normal consistency	Vicat plunger, 10 mm dia	Trial (P = 26–33%)	Penetration 5–7 mm from bottom
Initial setting	Vicat needle, 1 mm square	**0.85 P**	**≥ 30 min** (low heat ≥ 60 min)
Final setting	Needle with 5 mm annular collar	0.85 P	**≤ 600 min**
Soundness (lime)	Le Chatelier mould	**0.78 P**	**≤ 10 mm**
Soundness (lime + MgO)	Autoclave	P	**≤ 0.8%**
Fineness	Blaine apparatus / 90 µm sieve	—	**≥ 225 m²/kg** / residue ≤ 10%
Compressive strength	70.6 mm cube, vibrating machine	**(P/4 + 3)%**	Grade value at 28 d
Specific gravity	Le Chatelier flask	Kerosene	≈ 3.15

MEMORY TRICK

"**30 minutes to start, 10 hours to finish, 10 mm to swell**": IST ≥ 30 min, FST ≤ 600 min, Le Chatelier ≤ 10 mm. Water factors: **0.85 P → setting**, **0.78 P → soundness** ("Setting Eighty-five, Soundness Seventy-eight").

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Size of cement mortar cube? → **70.6 mm (50 cm² face)**.
- Le Chatelier apparatus is used to test? → **Soundness (free lime)**.
- Unsoundness due to MgO is detected by? → **Autoclave test**.
- Water added for the initial setting time test? → **0.85 P**.
- Standard sand used for cement mortar cubes? → **Ennore sand (IS 650)**.
- Minimum specific surface of OPC by Blaine's method? → **225 m²/kg**.

5.3 Aggregates ★★★

- Aggregates occupy **70–80%** of the volume of concrete. They are covered by **IS 383:2016**, and tested under **IS 2386 (Parts 1–8)**.
- **Fine aggregate** passes the **4.75 mm** IS sieve. **Coarse aggregate** is retained on 4.75 mm. **All-in aggregate** contains both.
- By origin, aggregates are natural (river sand, gravel, crushed rock) or manufactured. IS 383:2016 recognises **manufactured (crushed) sand**, **recycled concrete aggregate (RCA)**, and slag aggregates from iron, steel and copper slag.
- By shape: **rounded** gives the best workability and the least water. **Angular** gives better bond and strength but needs more water and paste. Flaky and elongated particles are undesirable.
- **Maximum size of coarse aggregate** (IS 456): it should not exceed **¼ of the minimum thickness** of the member, and should be **5 mm less than the minimum clear cover** or the clear bar spacing. **20 mm** is usual for RCC and up to 40 mm for mass work. A larger maximum size needs less water but reduces strength in rich mixes.

Fine aggregate grading zone (IS 383:2016)	% passing 600 µm sieve	Nature
Zone I	**15–34**	Coarsest
Zone II	**35–59**	Medium; most suitable for general RCC
Zone III	**60–79**	Fine
Zone IV	**80–100**	Finest; generally **not used for RCC** unless trial mixes justify it

- The zones are separated by the **% passing the 600 µm sieve**. As the zone number rises (I → IV), sand becomes **finer**, so the proportion of fine aggregate in the mix should be **reduced**.
- **Fineness Modulus (FM)** = Σ(cumulative % retained on the standard sieves) ÷ 100. The standard sieves are 80, 40, 20, 10, 4.75, 2.36, 1.18 mm and 600, 300, 150 µm. A higher FM means coarser aggregate. FM is an index, not a grading.

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Material	Fineness modulus
Fine sand	**2.2–2.6**
Medium sand	**2.6–2.9**
Coarse sand	**2.9–3.2** (FM > 3.2 is unsuitable)
Coarse aggregate	**5.5–8.0**
All-in aggregate	3.5–6.5

- **Bulking of sand**: moisture films around the particles push them apart, so damp sand occupies more volume. Bulking is **maximum at about 4–6% moisture** and amounts to **20–40%**; finer sand bulks more. **Saturated (inundated) sand shows no bulking**, as does fully dry sand. This matters for **volume batching**. Test: IS 2386 Part 3.
- **Flakiness index** = % by weight of particles whose **least dimension < 0.6 × mean dimension** (thickness gauge).
- **Elongation index** = % by weight of particles whose **greatest dimension > 1.8 × mean dimension** (length gauge).
- Both indices apply to aggregate larger than 6.3 mm. IS 383:2016 limits the **combined flakiness + elongation index to ≤ 40%**.
- **Specific gravity** of common aggregates is **2.6–2.8**, usually taken as 2.6–2.7. **Water absorption** is generally ≤ 2%; aggregates absorbing more must also pass the soundness test. Mix design uses the **SSD (saturated surface-dry)** condition.
- **Soundness of aggregate** (resistance to weathering) is tested with 5 cycles of **sodium sulphate** (loss ≤ **10%**) or **magnesium sulphate** (loss ≤ **15%**).

Mechanical test (IS 2386 Part 4)	Procedure in brief	Limit: wearing surfaces	Limit: other concrete
Crushing value	Aggregate passing 12.5 mm and retained on 10 mm, loaded to **400 kN in 10 min**; fines passing 2.36 mm as % of sample	**≤ 30%**	**≤ 45%**
Impact value	Hammer of 13.5–14 kg falling **380 mm, 15 blows**; fines passing 2.36 mm	**≤ 30%**	**≤ 45%**
Los Angeles abrasion value	Steel balls in a drum, **500 revolutions** at 30–33 rpm (1000 for gradings E–G); fines passing 1.70 mm	**≤ 30%**	**≤ 50%**
Ten percent fines value	Load that produces 10% fines	≥ 150 kN	≥ 50 kN

- The crushing value is **not reliable for aggregates with a crushing value above 30%**; for those, the ten percent fines test is used. For all these tests, a **lower value means stronger, tougher aggregate**.
- **Deleterious materials** are clay lumps, coal and lignite, shale, mica, organic impurities, salts and material finer than 75 µm. Limits: clay lumps ≤ 1%. Material finer than 75 µm in fine aggregate is ≤ 3% for natural sand and up to **15% for crushed / manufactured sand**. **Mica** reduces strength and workability. **Organic impurities** are checked with the **colour test (3% NaOH)**.
- **Alkali–Aggregate Reaction (AAR)**: **reactive silica** (opal, chalcedony, chert) reacts with the cement alkalis Na_2O and K_2O. The result is an expansive **alkali-silica gel**, which absorbs water and produces **map/pattern cracking**. It was first reported by **Stanton (USA, 1940)**. Control it with low-alkali cement (total Na_2O equivalent = $Na_2O + 0.658\ K_2O$ ≤ **0.6%**), pozzolans (fly ash, GGBS, silica fume), non-reactive aggregate and dry conditions. Tests: **mortar bar test** and chemical method (IS 2386 Part 7).
- **Manufactured sand (M-sand)** is crushed rock fines, made in VSI crushers. It is angular and needs more water or admixture. It is an alternative to river sand, which is restricted because of mining bans.

KEY FORMULAE

- Fineness modulus = Σ cumulative % retained (standard sieves) ÷ 100
- Bulking % = (Volume of moist sand − Volume of dry sand) ÷ Volume of dry sand × 100
- Aggregate impact / crushing value = (Wt passing 2.36 mm ÷ total wt of sample) × 100
- Water absorption = $(W_{SSD} - W_{oven\text{-}dry}) \div W_{oven\text{-}dry} \times 100$

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Bulking of sand is maximum at moisture content of about? → **4–6%**.
- Grading zones of fine aggregate are based on % passing which sieve? → **600 µm**.
- Fineness modulus of medium sand? → **2.6–2.9**.
- Maximum aggregate impact value for wearing surfaces? → **30%**.
- Flaky particle: least dimension less than? → **0.6 × mean dimension**.
- Alkali-aggregate reaction involves which constituent of aggregate? → **Reactive silica**.

5.4 Fresh Concrete & Workability ★★★

- **Abrams' law (1919)**: for fully compacted concrete, strength depends only on the **water–cement ratio**. $S = A / B^{w/c}$, where A and B are constants. A lower w/c gives higher strength, provided the concrete is fully compacted.
- **Gel–space ratio (Powers)**: strength is related to the ratio of hydrated cement gel volume to the space available. It describes strength better than w/c because it accounts for the degree of hydration.
- **Workability** is the ease of mixing, placing, compacting and finishing without segregation. Its main factor is the **water content**. Others are aggregate shape, texture, grading and size, the aggregate–cement ratio, admixtures (air

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entrainment and plasticisers raise it) and temperature and time. It is tested under **IS 1199 (Parts 1–7):2018**, which replaced IS 1199:1959.

KEY FORMULAE

- Abrams: $f_c = A \div B^{(w/c)}$
- Powers: $f_c = 240\ x^3$ (MPa), where gel–space ratio $x = 0.657\ \alpha \div (0.319\ \alpha + w/c)$ and α = degree of hydration
- Compacting factor = Wt of partially compacted concrete ÷ Wt of fully compacted concrete
- Flow (%) = (Spread dia − Original base dia) ÷ Original base dia × 100
- Maturity = $\Sigma\ (T + 11\ °C) \times \Delta t$ (°C·h); the datum is −11 °C (Plowman / Nurse–Saul)

Test	Measures / apparatus	Best suited for
Slump test	Frustum mould: **bottom 200 mm, top 100 mm, height 300 mm**. Filled in 4 layers, each given **25 strokes** of a 16 mm × 600 mm rod. The fall of the top is measured.	Medium to high workability; site control. **Not suitable for very dry or very wet mixes.**
Compacting factor	Two hoppers and a cylinder (150 mm dia × 300 mm). Results are a ratio between 0.7 and 1.0.	**Low workability**; a lab test, more sensitive and precise than slump
Vee-Bee consistometer	Time in seconds (**Vee-Bee degrees**) for the slumped cone to remould to a cylinder under vibration	**Very low workability** (stiff, dry mixes); good range 3–30 s
Flow table	Spread of concrete after repeated jolting (IS 1199 Part 2: 15 drops of 40 mm)	**High workability / flowing concrete**
SCC tests	**Slump flow** (550–850 mm), T_{500}, **V-funnel**, **L-box** ($H_2/H_1 \geq 0.8$), U-box, **J-ring**	Self-compacting concrete

Degree of workability	Slump (mm)	Compacting factor	Vee-Bee (s)	Typical use
Very low	0–25	**0.75–0.80**	> 12 (10–20)	Roads with power vibrators, blinding
Low	25–75	**0.80–0.85**	6–12	Mass concrete, lightly reinforced sections, hand-placed pavements, canal lining
Medium	50–100	**0.85–0.92**	3–6	Heavily reinforced slabs, beams and columns
High	100–150	**> 0.92** (≈ 0.95)	0–3	Trench fill, in-situ piling, congested sections
Very high	Collapse; use flow test	—	—	**Tremie concrete**, SCC

- IS 456 cl. 7.1 recommends slumps of 75–100 mm for **slipform and pumped concrete** and 100–150 mm for **trench fill and in-situ piling**.
- **Types of slump**: **true slump** (the cone subsides evenly), **shear slump** (one half slides down an inclined plane, which shows a **lack of cohesion**, so the test should be repeated), and **collapse slump** (a very wet or harsh mix).

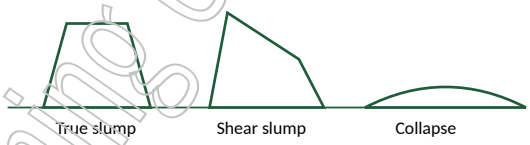

Fig 5.1 Types of slump. Only a true slump is a valid reading.

- **Segregation** is the separation of coarse aggregate from mortar. It is caused by a high free fall, a wet mix, over-vibration, poor grading or conveying over long distances. Limit the free fall to **≤ 1.5 m**; for deeper placing, use a chute, tremie or pipe.
- **Bleeding** is water rising to the surface, a form of segregation. It is caused by a high w/c, coarse cement or excess vibration. It is reduced by finer cement, air entrainment, pozzolans and a lower w/c.
- **Laitance** is the weak, milky layer of cement fines left on top by bleeding. It must be removed before the next lift, otherwise the construction joint is weak.
- **Compaction**: **each 1% of voids lowers strength by about 5–6%**. Vibrators: **needle (immersion)**, surface (screed), form (shutter), table. Insert needle vertically ~600 mm apart and withdraw slowly; over-vibration causes segregation.
- **Curing** keeps concrete moist and warm so that hydration continues. Methods: ponding, wet coverings (hessian, gunny bags), sprinkling, **membrane curing compound** (where water is scarce), polythene sheets, **steam curing** (for precast, accelerates strength) and autoclaving.

IS 456 cl. 13.5 – minimum moist curing	Normal weather	Dry and hot weather
OPC	**7 days**	**10 days**
Mineral admixtures or blended cements (PPC, PSC)	**10 days**	**14 days**

IS 456 cl. 11.3 – formwork stripping (OPC, 27 °C)	Time
Vertical faces of walls, columns, beams	**16–24 h**
Slab soffit (props left under)	**3 days**

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Beam soffit (props left under)	**7 days**
Props to slabs: span ≤ 4.5 m / > 4.5 m	**7 / 14 days**
Props to beams and arches: span ≤ 6 m / > 6 m	**14 / 21 days**

- **Hot weather concreting** (IS 7861 Part 1): slump loss, plastic shrinkage cracks, cold joints. Remedies: **chilled water or ice flakes**, cooled aggregate, retarders, night placing. Placing temperature **≤ 40 °C**.
- **Cold weather concreting** (IS 7861 Part 2): risk of early **freezing**. Remedies: heated water and aggregate, **accelerators**, air entrainment, insulation, RHC. Keep concrete **≥ 5 °C**.

MEMORY TRICK

Match each test to its workability: "**Vee-Bee = Very dry; CF = Comparatively dry (low); Slump = Site (medium); Flow = Fluid**." On the compacting-factor scale, **0.78–0.85–0.92–0.95** runs from very low to high.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Workability test best suited for very low workability concrete? → **Vee-Bee consistometer**.
- Dimensions of slump cone? → **200 mm bottom, 100 mm top, 300 mm high**.
- Shear slump indicates? → **Lack of cohesion / harsh mix**.
- Abrams' law relates strength to? → **Water–cement ratio**.
- Minimum curing period for OPC concrete per IS 456? → **7 days**.
- Weak milky layer formed on the top surface due to bleeding? → **Laitance**.

5.5 Admixtures & Special Concretes ★★☆

- **Chemical admixtures** are covered by **IS 9103:1999**. They are added in small doses, in % by mass of cement, at the time of mixing.

Chemical admixture	Typical materials	Effect / use
Accelerator	**Calcium chloride ($CaCl_2$)**, max ≈ 2%; triethanolamine; calcium formate	Faster setting and early strength; cold weather, early stripping, repairs. **$CaCl_2$ corrodes steel: never use it in prestressed concrete** and avoid it in RCC.
Retarder	Gypsum, **sugar**, starch, lignosulphonates, hydroxy-carboxylic acids (tartaric, citric)	Delays setting; **hot weather**, RMC, long hauls, large pours, avoiding cold joints. About 0.05% sugar retards; an overdose can stop setting altogether.
Plasticiser (water reducer)	**Lignosulphonates**, hydroxylated carboxylic acids	Water reduction **5–15%**, or higher slump at the same w/c
Superplasticiser (high-range water reducer)	**SNF** (sulphonated naphthalene formaldehyde), **SMF** (melamine), **PCE** (polycarboxylate ether, the newest generation)	Water reduction **15–30%** (PCE up to ~40%); used for HPC, SCC and flowing concrete. Slump loss sets in after 30–60 min.
Air-entraining agent	**Neutralised vinsol resin**, natural resins, fats, detergents	Introduces tiny, stable, disconnected bubbles, **3–6% air**. Gives **freeze–thaw resistance**, better workability and less bleeding. **Each 1% of air lowers strength by about 5%.**

Mineral admixture (pozzolan / SCM)	Source & key data	Use / benefit
Fly ash (IS 3812 Part 1)	Thermal-power plant (ESP) ash. **Class F** is siliceous with low lime (bituminous coal); **Class C** is calcareous with high lime (lignite).	Up to 35% in PPC. Better workability, lower heat, slower early strength, better durability.
Silica fume (micro-silica, IS 15388)	By-product of silicon and ferro-silicon alloy production. **SiO_2 ≥ 85%**; particles ~0.1 µm (≈ **100 times finer** than cement); surface area ~20,000 m²/kg.	**5–10%** replacement; very high strength and low permeability; **HPC**. Needs a superplasticiser.
GGBS (IS 16714:2018)	Ground granulated blast-furnace slag from steel plants; latent hydraulic	Up to **70%** (PSC); sulphate and chloride resistance; low heat; light colour
Metakaolin (IS 16354)	Calcined kaolin clay at ~700–800 °C	Highly reactive; strength and durability
Rice husk ash	Controlled burning of rice husk; amorphous silica ~85–90%	Highly reactive pozzolan

- A **pozzolan** has no cementing value by itself. In the presence of water it reacts with the **$Ca(OH)_2$** released by hydration to form extra C-S-H; this is the **pozzolanic reaction**, and it is slow.

Special concrete	Key facts
Ready-Mixed Concrete (RMC)	**IS 4926:2003**. Batched at a central plant and delivered by transit mixer (agitator truck). Quality-controlled, saves storage space, and suits congested urban sites.

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Self-Compacting Concrete (SCC)	Developed by **Okamura (Japan, 1986)**. It flows under its own weight with no vibration. It needs a high powder content, superplasticiser and a VMA, with MSA ≤ 20 mm. Tested by slump flow, L-box, V-funnel and J-ring.
High Performance Concrete (HPC)	Low w/c (< 0.35–0.40), silica fume plus superplasticiser; high strength with high durability
Fibre-Reinforced Concrete (FRC)	Steel, glass, polypropylene, carbon or nylon fibres, 0.5–2% by volume; aspect ratio (l/d) ≈ **50–100**. Improves tensile and flexural strength, impact resistance, crack control and toughness. Used in pavements, tunnel linings and industrial floors.
Lightweight concrete	Density ≈ 300–1850 kg/m³. Three kinds: lightweight aggregate concrete (pumice, LECA, sintered fly ash); **aerated / cellular** (Al powder or foam; AAC blocks); **no-fines**. Good thermal insulation.
High-density (heavyweight) concrete	Barytes, magnetite, haematite or steel punchings; density ≈ **3000–5000 kg/m³**; used for **radiation shielding** (nuclear plants, X-ray rooms).
Ferrocement	Pioneered by **P.L. Nervi**. Rich cement mortar (1:1.5 to 1:2) on **closely spaced layers of fine wire mesh**, thickness ~10–40 mm. Used for water tanks, boats, shells and roofing.
Shotcrete / Guniting	Mortar or concrete sprayed pneumatically at high velocity. **Guniting = dry-mix process**, in which **water is added at the nozzle**; it uses mortar or fine aggregate. Shotcrete may be wet- or dry-mix and can include coarse aggregate up to ~10 mm. Used for tunnel linings, slope protection and repairs.
Pumped concrete	Needs a cohesive mix with adequate fines and cement content; slump ≈ 75–100 mm. Used for high-rise work.
Polymer concrete	Three kinds: **PIC** (polymer-impregnated: hardened concrete impregnated with monomer, then polymerised); **PC** (polymer binder only, no cement); **PMC/PCC** (latex modified). High strength and chemical resistance.
No-fines concrete	Cement plus single-size coarse aggregate with **no sand**, 1:6 to 1:10. It is porous, light and has no capillary rise; used for **pervious pavements** and walls. It is not used for RCC.
Roller-Compacted Concrete (RCC)	A **zero-slump**, dry, lean mix compacted with **vibratory rollers**. Built fast and cheaply for **dams** and heavy pavements.
Geopolymer concrete	Term coined by **Davidovits**. **No OPC**: fly ash or GGBS is activated by **NaOH + sodium silicate**. Low CO_2, and often heat-cured.

MEMORY TRICK

"**$CaCl_2$ Cures Cold, but Corrodes**": it is an accelerator for cold weather that rusts steel. "**Sugar Slows**": it is a retarder. "**Vinsol = Voids**": it is an air-entrainer.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Most common accelerator? → **Calcium chloride**.
- Admixture used to improve freeze–thaw resistance? → **Air-entraining agent (vinsol resin)**.
- In guniting, water is added? → **At the nozzle**.
- IS code for ready-mixed concrete? → **IS 4926**.
- Silica fume is a by-product of? → **Silicon / ferro-silicon alloy industry**.
- Concrete with no fine aggregate is called? → **No-fines concrete**.

5.6 Mix Design ★★★

- **Mix design** means choosing the proportions of cement, water, fine and coarse aggregate and admixtures to achieve the required **strength, workability and durability** at minimum cost. Indian practice follows **IS 10262:2019**, which replaced the 2009 edition.
- **Nominal mix**: proportions are fixed by volume. IS 456 permits it only up to **M20**.
- **Design mix**: proportions are found by design and trial mixes, with performance specified. It is preferred, and is compulsory for M25 and above.

KEY FORMULAE

- Target mean strength: $f'_{ck} = f_{ck} + 1.65\ S$ **or** $f'_{ck} = f_{ck} + X$, **whichever is higher** (IS 10262:2019)
- 1.65 corresponds to **5% of results allowed below f_{ck}** (characteristic strength).
- Absolute volume: $V_{cement} + V_{water} + V_{admixture} + V_{aggregate} = 1$ − air content; each V = mass ÷ (SG × 1000)
- Dry volume of ingredients ≈ **1.54 × wet volume** (1.52–1.57 used) for concrete; ≈ 1.27–1.33 for mortar
- Cement for 1 m³ of 1:a:b = 1.54 ÷ (1 + a + b) m³ × 1440 kg/m³

Grade (IS 10262:2019)	Assumed S (Table 2), MPa	Factor X (Table 1), MPa
M10, M15	**3.5**	**5.0**
M20, M25	**4.0**	**5.5**
M30 – M60	**5.0**	**6.5**
M65 and above	**6.0**	**8.0**

- The assumed S applies at good site control. The actual S should come from **at least 30 test results**. Example: M25 gives 25 + 1.65 × 4 = **31.6 MPa**, while 25 + 5.5 = 30.5. The target is the higher figure, **31.6 MPa**.

IS 10262:2019 – steps	Key data
1. Target mean strength	f_{ck} + 1.65 S or f_{ck} + X (the higher)

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2. Approximate air content (entrapped)	MSA 10 mm: 1.5%; **20 mm: 1.0%**; 40 mm: 0.8%
3. Water–cement ratio	From the w/c–strength curves for the cement's 28-day strength. Check it against the **IS 456 Table 5 maximum w/c** and adopt the lower value.
4. Water content	For 50 mm slump with angular aggregate: **10 mm: 208 kg, 20 mm: 186 kg, 40 mm: 165 kg** per m^3. Add **3% for every 25 mm extra slump**. Reduce for rounded aggregate or water-reducing admixtures (superplasticiser ≈ 20% or more).
5. Cementitious content	Water ÷ w/c. Check the **IS 456 minimum** and the maximum of **450 kg/m^3** (OPC).
6. Coarse aggregate proportion	Volume of CA per unit volume of total aggregate at w/c = 0.5. For 20 mm MSA: **Zone I 0.60, II 0.62, III 0.64, IV 0.66**. Adjust by **±0.01 for every ∓0.05 change in w/c**; reduce by 10% for pumpable concrete.
7. Mix calculations	Absolute volume method, with aggregates in SSD condition
8. Trial mixes	Adjust for workability and strength, and correct for field moisture and absorption

IS 456 Table 5 (RCC)	Min cement (kg/m^3)	Max free w/c	Min grade
Mild	300	0.55	**M20**
Moderate	300	0.50	M25
Severe	320	0.45	M30
Very severe	340	0.45	M35
Extreme	360	0.40	M40

Nominal mix (IS 456 Table 9)	Proportion (C : FA : CA)	Total aggregate per 50 kg cement	Water per 50 kg cement
M5	**1 : 5 : 10**	800 kg	60 L
M7.5	**1 : 4 : 8**	625 kg	45 L
M10	**1 : 3 : 6**	480 kg	34 L
M15	**1 : 2 : 4**	330 kg	32 L
M20	**1 : 1.5 : 3**	250 kg	30 L

Group (IS 456 Table 2)	Grades
Ordinary concrete	**M10 – M20**
Standard concrete	**M25 – M55**
High strength concrete	**M60 – M80**

- In "M20", **M** stands for mix and **20** for the **characteristic compressive strength in N/mm²** of a 150 mm cube at 28 days. Characteristic strength is the value below which **not more than 5%** of results are expected to fall.
- Worked quantity for **1 m^3 of M20 (1:1.5:3)**, taking the dry volume as 1.54 m^3: cement = 1.54/5.5 = 0.28 m^3 = **403 kg ≈ 8 bags**; sand = 0.42 m^3; coarse aggregate = **0.84 m^3**.

CODE UPDATE

IS 10262:2019 extended the assumed S of 5.0 MPa to M30–M60 (it was 5.0 for M30–M50 in 2009), added S = 6.0 MPa for M65 and above, and introduced the factor **X**; the target is now the higher of f_{ck} + 1.65S and f_{ck} + X. It also added guidance for **SCC, mass concrete and high-strength concrete (up to M100)**, and for fly ash and GGBS mixes.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Target mean strength for M20 (S = 4)? → **20 + 1.65 × 4 = 26.6 MPa**.
- Nominal mix proportion of M20? → **1 : 1.5 : 3**.
- Number of cement bags per m^3 of M20 nominal mix? → **≈ 8 bags**.
- Maximum grade for which nominal mix is permitted (IS 456)? → **M20**.
- Standard concrete range per IS 456? → **M25 – M55**.
- Latest IS code for concrete mix proportioning? → **IS 10262:2019**.

5.7 Hardened Concrete & Testing ★★★

- **Compressive strength**: the standard **cube is 150 mm**; 100 mm cubes are allowed when MSA ≤ 20 mm. **Cylinders are 150 mm × 300 mm** (ACI/BS EN). **Cylinder strength ≈ 0.8 × cube strength**; the cube gives a higher value because of platen restraint.
- **Test result** = average of **3 specimens**. If any individual result varies by more than **±15%** of the average, the result is invalid.

Sampling frequency (IS 456 cl. 15.2.2)	Number of samples
1 – 5 m^3	**1**
6 – 15 m^3	**2**
16 – 30 m^3	**3**
31 – 50 m^3	**4**
51 m^3 and above	**4 + 1** for each additional 50 m^3 or part

- A sample means **3 cubes**, and at least one sample is taken per shift. Additional samples may be taken for 7-day strength.

IS 456 Table 11 – acceptance (compressive)	Mean of 4 non-overlapping consecutive results	Any individual result
M15 and above (as amended – current)	≥ f_{ck} + 0.825 S (S rounded to 0.5) or **f_{ck} + 3** MPa, whichever is greater	≥ **f_{ck} – 3** MPa
Original 2000 text, M20 and above (older MCQ keys)	≥ f_{ck} + 0.825 S or f_{ck} + 4 MPa, whichever is greater	≥ f_{ck} – 4 MPa

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- Amended Table 11 note: for quantities up to **30 m³** (fewer than 4 samples), the mean of all samples must be ≥ $\mathbf{f_{ck} + 4}$ MPa.
- Flexural strength is acceptable when the mean of 4 results is ≥ f_{cr} + 0.3 MPa and every individual result is ≥ f_{cr} − 0.3 MPa.
- **Split tensile test** (Brazilian test): a cylinder is loaded along its diameter. Its value is about 0.6–0.7 of the flexural strength.
- **Flexural test**: a beam of 150 × 150 × 700 mm on a 600 mm span (or 100 × 100 × 500 mm on a 400 mm span) under **two-point (third-point) loading**. This gives a **constant bending moment and zero shear** over the middle third. The result is the **modulus of rupture**, which is higher than the split tensile strength.
- Direct tensile strength is ≈ **8–12%** of compressive strength. The order is **direct tension < split tensile < flexural**.

KEY FORMULAE

- Flexural strength (IS 456): $f_{cr} = \mathbf{0.7\sqrt{f_{ck}}}$
- Modulus of elasticity (IS 456): $E_c = \mathbf{5000\sqrt{f_{ck}}}$ (short term)
- Modulus of rupture (crack in middle third): $f_b = P\,L \div (b\,d^2)$. If the crack is outside the middle third with a = 110–133 mm (150 mm beam): $f_b = 3\,P\,a \div (b\,d^2)$; if a < 110 mm, the result is discarded.
- Split tensile strength: $f_{ct} = \mathbf{2P \div (\pi\,D\,L)}$
- Long-term (effective) modulus: $E_{ce} = E_c \div (1 + \theta)$, where θ = creep coefficient
- Creep coefficient θ = creep strain ÷ elastic strain

NDT method	Principle / code	Remarks
Rebound hammer (Schmidt hammer)	Surface hardness gives a rebound number, read off a correlation curve. **IS 516 (Part 5/Sec 4):2020**, earlier IS 13311 (Part 2).	Quick and cheap. Affected by surface moisture, **carbonation (over-estimates)**, smoothness and hammer angle. It reads only the surface layer, ~30 mm.
Ultrasonic Pulse Velocity (UPV)	Travel time of a 50–54 kHz pulse, giving V = L/t. **IS 516 (Part 5/Sec 1):2018**, earlier IS 13311 (Part 1).	Shows homogeneity, cracks, voids and honeycombing. Direct (opposite-face) transmission is best; semi-direct and indirect (surface) transmission are also used.
Core test	IS 516 (Part 4):2018	Semi-destructive; the most reliable in-situ strength
Half-cell potential	Corrosion probability of rebar (copper/copper-sulphate electrode)	More negative than **−350 mV** means > 90% probability of corrosion; less negative than −200 mV means low probability.
Carbonation depth	**Phenolphthalein** sprayed on a fresh broken surface	**Pink = uncarbonated** (pH > ~9); colourless = carbonated

UPV (km/s) – classic IS 13311 (Part 1) grading	Concrete quality
Above 4.5	**Excellent**
3.5 – 4.5	**Good**
3.0 – 3.5	**Medium**
Below 3.0	**Doubtful**

- IS 516 (Part 5/Sec 1):2018 replaced this with a revised criterion (for M25 and above): **above 4.40 km/s Excellent; 3.75–4.40 Good; 3.00–3.75 Doubtful; below 3.00 Poor**. In MCQs, the classic four-level table above is still what is usually asked.
- **Core test**: core dia ≥ **3 × MSA**, preferably 100 or 150 mm, with **L/D = 2** preferred; L/D below 2 is corrected. The equivalent cube strength is about 1.25 × the corrected cylinder strength. **IS 456 cl. 17.4.3**: concrete is acceptable if the **average equivalent cube strength of the cores ≥ 85%** of the cube strength of the grade and **no individual core is < 75%**.

Creep coefficient θ (IS 456 cl. 6.2.5.1) – age at loading	θ
7 days	**2.2**
28 days	**1.6**
1 year	**1.1**

- **Creep** = time-dependent strain under **sustained constant stress**. It **increases** with higher stress, higher w/c and paste content, lower humidity and **earlier age at loading**; decreases with stiffer aggregate. Partly recoverable; causes long-term deflection and loss of prestress.
- **Relaxation** is the loss of stress at constant strain.
- **Shrinkage** = volume decrease without load; total strain **0.0003** (IS 456 cl. 6.2.4.1) in absence of data. Types: **plastic** (fresh concrete, prevented by early curing), **drying** (loss of gel-pore water, partly reversible), **autogenous** (self-desiccation, low w/c) and **carbonation**. Increases with water and cement content.
- **Thermal expansion coefficient** of concrete is ≈ $\mathbf{10 \times 10^{-6}}$ **/ °C** (range 6–12 × 10^{-6}), close to steel at 12 × 10^{-6}. That closeness is why the two work together in RCC.
- **Durability** depends mainly on **low permeability**: low w/c, adequate cement, full compaction, good curing and adequate **cover**. Below w/c ≈ 0.4 capillary pores become discontinuous.
- **Carbonation**: $CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$. The pH drops from about 12.5–13 to **< 9**, the passive film on the steel is lost, and the bars corrode. Depth grows roughly with √(time).
- **Chloride attack**: Cl^- breaks the passive film even at high pH → **pitting corrosion**; rust occupies **2–6 times** the volume of steel, spalling the cover.

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- **Sulphate attack**: sulphates react with $Ca(OH)_2$ and C_3A hydrates → expansive **gypsum and ettringite**. Remedy: **SRC**, PSC/PPC, low w/c. Total SO_3 in mix ≤ **4% by mass of cement** (IS 456). Freeze–thaw is resisted by air entrainment.

Max acid-soluble chloride as Cl (IS 456 Table 7)	kg/m³ of concrete
Prestressed concrete	**0.4**
RCC, or PCC with embedded metal	**0.6**
Concrete with no embedded metal	**3.0**

CODE UPDATE

IS 516 has been restructured into parts. **Part 1/Sec 1:2021** covers compressive, flexural and split tensile strength. **Part 4:2018** covers cores. **Part 5** covers NDT: **Sec 1:2018** UPV and **Sec 4:2020** rebound hammer, superseding IS 13311 Parts 1 and 2. Fresh-concrete tests are now **IS 1199 (Parts 1–7):2018**.

MEMORY TRICK

"**2.2 – 1.6 – 1.1 at 7 – 28 – 365**": the creep coefficient falls as the loading age rises. "**85–75**" is the core rule (average – individual). "**0.4 – 0.6 – 3**" is the chloride rule for PSC – RCC – PCC.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Creep coefficient for loading at 28 days per IS 456? → **1.6**.
- Total shrinkage strain in absence of data (IS 456)? → **0.0003**.
- Number of samples for 40 m³ of concrete? → **4**.
- UPV above 4.5 km/s indicates concrete quality? → **Excellent**.
- Flexural strength of M25 concrete per IS 456? → **$0.7\sqrt{25}$ = 3.5 MPa**.
- Indicator used to find carbonation depth? → **Phenolphthalein**.

5.8 Prestressed Concrete ★★★

- **Prestressing** means applying a permanent internal compressive force, usually by tensioned high-strength steel tendons. It counteracts the tensile stresses from external loads, so **the whole section stays effective** and cracking is controlled.
- **Eugene Freyssinet** (France, 1928) is the "father of prestressed concrete". He recognised that **high-tensile steel** is essential. The Indian code is **IS 1343:2012** (Prestressed Concrete – Code of Practice), which replaced the 1980 edition.
- **Why high-tensile steel**: total losses are about **200–250 N/mm²**. Mild steel (f_y ≈ 250) would lose almost all its prestress. High-tensile steel has f_{pu} ≈ **1500–2000 N/mm²**.
- **Prestressing steel**: cold-drawn **plain or indented wires (IS 1785)**, usually 2.5–8 mm; stranded wire such as 7-ply strand of 12.7 and 15.2 mm (**IS 6006**, and **IS 14268** for low-relaxation strand); **high-tensile bars (IS 2090)**. A **tendon** is the general term for a wire, strand or bar used to prestress.
- **Minimum grade of concrete (IS 1343:2012)**: **M30 for post-tensioned** and **M40 for pre-tensioned** members. High strength is needed for bond and transfer, for the high bearing stresses at anchorages, and to reduce creep, shrinkage and elastic-shortening losses.

Aspect	Pre-tensioning	Post-tensioning
Sequence	Tendons are tensioned between abutments **before casting**; they are released after the concrete hardens	Concrete is cast with **ducts/sheaths**; tendons are tensioned **after hardening** and anchored at the ends
Force transfer	**By bond** between steel and concrete (over the transmission length)	**By end anchorages** (bearing), then grouting
Cable profile	Mostly **straight** (or harped/deflected)	**Curved / parabolic** profiles are easy
Suited to	**Factory precast**, small to medium members: **railway sleepers**, electric poles, hollow-core slabs, piles	**In-situ, large spans**: bridges, box girders, large beams, water tanks
Typical system	**Hoyer long-line** system	Freyssinet, Magnel–Blaton, Gifford–Udall, Lee–McCall, BBRV, CCL
Anchorages and ducts	Not needed (temporary anchors at the bed)	Needed; costly
Losses	**Greater**, about 20–25% (elastic shortening is full)	**Smaller**, about 15–20%, but includes friction and anchorage slip
Min concrete grade (IS 1343)	**M40**	**M30**

Prestressing system	Type	Anchorage principle
Hoyer (Germany)	Pre-tensioning	**Long-line method**: wires stretched between two abutments far apart, so several members are cast in one line and separated after release
Freyssinet	Post-tensioning	**Conical wedges**: a serrated male cone in a female cone; groups of 8–12 wires of 5 or 7 mm; double-acting jack
Magnel–Blaton (Belgium)	Post-tensioning	**Flat steel wedges in sandwich plates**; each wedge anchors 2 wires, and each sandwich plate takes up to 8 wires
Gifford–Udall (UK)	Post-tensioning	**Split-cone wedge** in a barrel; **each wire anchored individually**

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Lee–McCall (UK)	Post-tensioning	**High-tensile alloy bars** with threaded ends, anchored by **nuts** bearing on plates
BBRV (Switzerland)	Post-tensioning	**Cold-formed button heads** on the wires

KEY FORMULAE

- Fibre stresses: $f = P/A \pm P\,e/Z \mp M/Z$ (top: $P/A - Pe/Z_t + M/Z_t$; bottom: $P/A + Pe/Z_b - M/Z_b$)
- Elastic shortening loss = $\mathbf{m\,f_c}$, where $m = E_s/E_c$ and f_c = concrete stress at the tendon level
- Post-tensioned, n tendons stressed one by one: average loss ≈ ½ × (loss of the first tendon), i.e. $(n - 1)/(2n) \times m\,f_c$
- Shrinkage loss = $\varepsilon_{sh} \times E_s$; creep loss = $\theta \times m \times f_c$ (= $\varepsilon_{cc}\,E_s$)
- Friction: $P_x = P_0\,e^{-(\mu\alpha + kx)}$, where μ = coefficient of friction (curvature), α = cumulative angle (rad), k = wobble coefficient per m
- Anchorage slip loss = $\mathbf{\Delta\,E_s \div L}$ (Δ = slip, L = cable length; this loss matters most in **short cables**)
- Load balancing (parabolic cable, sag e): equivalent upward load $w_b = \mathbf{8\,P\,e \div L^2}$
- Kern distances: $k_t = Z_b/A$, $k_b = Z_t/A$. Rectangle: **h/6** each side of the centroid (middle third)
- Shift of pressure line = M ÷ P

Loss of prestress	Pre-tensioned	Post-tensioned	Typical % (T.Y. Lin) pre / post
Elastic shortening of concrete	**Yes**	**Only if tendons are stressed one after another**; nil if all are stressed together	4 / 1
Creep of concrete	Yes	Yes	6 / 5
Shrinkage of concrete	Yes	Yes (less, because the concrete is older at transfer)	7 / 6
Relaxation of steel	Yes	Yes	8 / 8
Friction (length and wobble effect, curvature)	**No**	**Yes**	— / extra
Anchorage slip	No (generally)	**Yes**	— / extra
Total (time-dependent + immediate)	Pre-tensioned > post-tensioned		**≈ 25 / 20** (commonly quoted 15–20% overall)

- **Immediate (short-term) losses** are elastic shortening, friction and anchorage slip. **Time-dependent losses** are creep, shrinkage and relaxation.
- The classic IS 1343:1980 values used in textbooks:
  - Shrinkage strain: **0.0003** for pre-tensioned, and **0.0002 / $\log_{10}(t + 2)$** for post-tensioned, where t = age in days at transfer.
  - μ (curvature friction): **0.55** for steel moving on concrete, 0.30 for steel on steel fixed to the duct, 0.25 for steel on lead.
  - k (wobble): ≈ 0.0015–0.0050 per m.
  - Relaxation: nil at 0.5 f_{pu}, rising to about 35, 70 and 90 N/mm² at 0.6, 0.7 and 0.8 f_{pu}. **Low-relaxation strands** reduce it.
- **Load balancing method (T.Y. Lin, 1963)**: the prestress is chosen so that the cable's upward force balances a chosen part of the load, often the dead load. Under the balanced load the beam carries only uniform axial compression (**P/A**), with no bending and no deflection. A parabolic cable balances a **UDL**; a harped cable balances **point loads**.
- **Pressure line (C-line / thrust line)** is the locus of the resultant compression in the concrete. At transfer it coincides with the cable. Under load it shifts by **M/P** towards the compression face. If the C-line stays **within the kern**, there is **no tension** anywhere in the section.
- **Kern (core)** is the zone within which a compressive force produces no tension. For a rectangle it is the **middle third (h/6 each side)** and, in plan, a rhombus. For a solid circle it is a circle of **D/8** radius (kern diameter D/4).
- **Cable profiles**:
  - **Straight**: concentric or eccentric (pre-tensioned).
  - **Parabolic**: matches the BMD of a UDL; maximum eccentricity at midspan and zero at the supports of a simply supported beam.
  - **Harped / trapezoidal**: for point loads.
  - **Concordant cable**: produces **no secondary moments** in an indeterminate (continuous) beam. A **linear transformation** of a cable profile, with the end points unchanged, does not alter the pressure line.

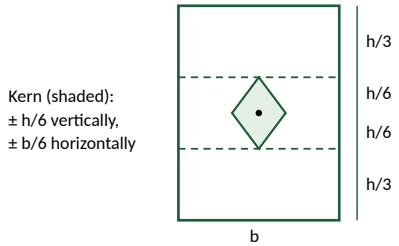

Fig 5.2 The kern of a rectangular section is a rhombus inside the middle third. A force inside it causes no tension.

- **End block (anchorage zone)**: in post-tensioned members the concentrated anchorage force spreads into the section over a length about **equal to the depth**. In this zone, **transverse tensile stresses** arise: **bursting tension** along the line of the force inside the zone, and **spalling tension** near the loaded face. They are resisted by **mesh or spiral (helical) reinforcement** behind the anchorage. Analysis methods are those of Magnel, Guyon, Rowe and Zielinski.

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- Bursting force, IS 1343: F_{bst}/P_k = 0.23, 0.20, 0.17, 0.14 and 0.11 for y_{po}/y_o = 0.3, 0.4, 0.5, 0.6 and 0.7. A **smaller bearing plate** (lower ratio) gives a **larger bursting force**.
- **Transmission length** (pre-tensioned) is the length over which prestress builds up by bond from the end. Classic IS 1343 values: **100 Φ for plain/indented wires, 65 Φ for crimped wires, 30 Φ for strands**. After release, the wire swells laterally at the ends (Poisson's effect), which gives a wedge grip called the **Hoyer effect**.

Classification (IS 1343)	Tensile stress / cracking under service load
Type / Class 1 (full prestressing)	**No tensile stress** allowed
Type / Class 2 (limited prestressing)	Tensile stress allowed within limits, but **no visible cracking**
Type / Class 3 (partial prestressing)	Tensile stress allowed and **cracks permitted**, with crack width limited (≈ 0.1–0.2 mm); untensioned steel is also provided

MEMORY TRICK

"**PRE has no F-A**": pre-tensioning has **no Friction and no Anchorage slip**. "**POST has no E**": post-tensioning has **no Elastic shortening** if all tendons are pulled at once. Systems: "**Freyssinet = cone, Magnel = sandwich, Gifford = single wire, Lee-McCall = bar and nut, Hoyer = long line**."

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Loss of prestress that does not occur in pre-tensioned members? → **Friction loss (and anchorage slip)**.
- Minimum grade of concrete for pre-tensioned members (IS 1343:2012)? → **M40**.
- Hoyer system is used for? → **Pre-tensioning (long-line method)**.
- Lee–McCall system uses? → **High-tensile bars anchored by threaded nuts**.
- Upward load due to a parabolic cable of eccentricity e? → **$8Pe/L^2$**.
- Kern distance of a rectangular section from the centroid? → **h/6**.

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6. Soil Mechanics, Foundation Engineering & Soil Improvement

NOTE

Geotechnical engineering gives roughly 6–9 of the 60 questions in most civil AE/JE papers. A warehouse sits on large slabs and isolated or pile foundations, often on black cotton or soft alluvial soil, so CWC papers also ask about bearing capacity, settlement limits and ground improvement. Most marks come from phase-relation numericals, consistency indices, Darcy and flow nets, T_v values, Terzaghi factors and IS 2720 / IS 6403 / IS 2911 facts.

6.1 Soil Formation, Phase Relations & Index Properties ★★★

- Soil forms by the **weathering** of rock. **Physical (mechanical) weathering** (temperature change, frost, abrasion) produces **coarse soils** with the same minerals as the parent rock. **Chemical weathering** (oxidation, hydration, carbonation, leaching) produces **clay minerals**.
- **Residual soil** stays where it formed. Examples: **laterite** (leached in hot humid climates and rich in Fe/Al oxides) and **black cotton soil** (from **Deccan trap basalt**, rich in montmorillonite).
- **Transported soil** is carried away from its parent rock and deposited elsewhere.

Transporting agent	Soil name	Key feature
Water (rivers)	**Alluvial** (e.g. Indo-Gangetic plain)	Stratified, sorted
Wind	**Aeolian**: **loess**, dune sand	Loess: uniform silt, stands in vertical cuts, **collapsible** on wetting
Glacier (ice)	**Glacial** till/drift, boulder clay, moraine, esker	**Very poorly sorted** (all sizes mixed)
Lakes	**Lacustrine**	**Varved clays** (alternate silt/clay layers)
Sea	**Marine**	Soft, highly compressible clays (e.g. Mumbai, Kochi coasts)
Gravity	**Colluvial** (talus, scree)	Angular fragments at the foot of slopes

- Other soil names: **bentonite** = montmorillonite clay formed from **volcanic ash**; **marl** = calcareous clay; **peat** = fibrous organic soil, the most compressible; **muck** = decomposed organic soil; **caliche/kankar** = cemented calcareous soil.
- **Soil structure**: single-grained (sands), **honeycomb** (silts), **flocculated** (clays, edge-to-face contact, made by compaction on the dry side), **dispersed** (face-to-face contact, made by compaction on the wet side or by remoulding).
- Clay minerals are built from **silica tetrahedral** sheets and **gibbsite (Al) / brucite (Mg) octahedral** sheets.

Mineral	Structure / bond	Specific surface	Swelling	Activity
Kaolinite	1:1, strong **hydrogen bond**	≈ 10–20 m^2/g	Least	≈ 0.4 (0.3–0.5)
Illite	2:1, **potassium (K^+)** bond	≈ 80–100 m^2/g	Moderate	≈ 0.5–1.3
Montmorillonite	2:1, weak van der Waals bond, water enters between layers	≈ **800 m^2/g**	**Maximum**	1–7 (Na-mont. ≈ 7)

KEY FORMULAE – PHASE RELATIONS

- Void ratio $e = V_v/V_s$ (can exceed 1). Porosity $n = V_v/V$ (always < 1). **$n = e/(1+e)$, $e = n/(1-n)$**
- Water content $w = W_w/W_s$ (on the dry-weight basis, so it can exceed 100%). Degree of saturation $S = V_w/V_v$
- **$S \cdot e = w \cdot G$**. For a saturated soil, **$e = wG$**
- Air content $a_c = V_a/V_v = 1 - S$. Percentage air voids $n_a = V_a/V = n \cdot a_c$
- Bulk unit weight $\gamma = (G + Se)\gamma_w/(1+e)$. Dry unit weight **$\gamma_d = G\gamma_w/(1+e) = \gamma/(1+w)$**
- Saturated unit weight $\gamma_{sat} = (G+e)\gamma_w/(1+e)$. Submerged unit weight **$\gamma' = \gamma_{sat} - \gamma_w = (G-1)\gamma_w/(1+e)$**
- $\gamma_d = (1 - n_a)G\gamma_w/(1 + wG)$. With $n_a = 0$ this gives the zero air voids line.
- Order of unit weights: **$\gamma_{sat} \geq \gamma \geq \gamma_d > \gamma'$**. γ' is about $\frac{1}{2}\gamma_{sat}$.
- Relative density (density index) **$D_r = (e_{max} - e)/(e_{max} - e_{min})$** $= [(\gamma_d - \gamma_{d,min})/(\gamma_{d,max} - \gamma_{d,min})] \cdot (\gamma_{d,max}/\gamma_d)$

- **D_r classes**: 0–15% very loose, 15–35% loose, 35–65% medium, 65–85% dense, 85–100% very dense. D_r applies to **cohesionless soils only** (IS 2720 Part 14:1983).
- **Specific gravity G** (IS 2720 Part 3:1980). Use the **density bottle (50 ml)** for fine soils and the **pycnometer (≈ 900 ml)** for coarse soils. Typical values: sand **2.65**, clay 2.70–2.80, organic soil < 2.0. $G = (W_2-W_1)/[(W_2-W_1) - (W_3-W_4)]$. Standard temperature is **27 °C**.
- **Water content** (IS 2720 Part 2:1973): oven drying at **105–110 °C for 24 h** is the standard method. Use **60–80 °C** for organic or gypseous soils. Rapid methods: calcium carbide (moisture meter), sand bath, alcohol, torsion balance, radiation.

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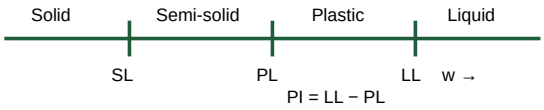

Consistency (Atterberg) limits on a water-content scale

Limit / index	Definition / test (IS 2720 Part 5:1985, Part 6:1972)
Liquid limit (LL)	Casagrande device: w at which a groove (≈ 12–13 mm closure length) closes in **25 blows**, fall height 10 mm, 2 blows/s. Cone penetrometer (IS): 31° cone, 148 g, w at **25 mm** penetration. (BS: 80 g, 30° cone, 20 mm.) Shear strength at LL ≈ **2.7 kPa** (≈ 1.7–2.7 kPa).
Plastic limit (PL)	w at which a thread just crumbles when rolled to **3 mm** diameter. Strength at PL ≈ 100 × that at LL.
Shrinkage limit (SL)	Lowest w at which the soil is still saturated. Below SL, further drying causes **no volume change**. Volume is measured by **mercury** displacement.
Plasticity index	**PI = LL − PL**. 0 = non-plastic, < 7 low, 7–17 medium, > 17 high plasticity
Liquidity index	**I_L = (w − PL)/PI**. I_L > 1 means liquid state; I_L < 0 means semi-solid
Consistency index	**I_C = (LL − w)/PI**. **$I_L + I_C = 1$**. I_C = 1 at PL, I_C = 0 at LL
Flow index	**$I_f = (w_1 - w_2)/\log(N_2/N_1)$**, the slope of the flow curve (w vs log N)
Toughness index	**I_t = PI/I_f**, usually 0–3. Less than 1 means friable at PL.
Shrinkage ratio	SR = $W_d/(V_d\gamma_w)$, equal to the mass specific gravity of the dry pat. **SL = (1/SR − 1/G) × 100%**
Activity (Skempton)	**A = PI / (% clay finer than 2 µm)**. < 0.75 inactive, 0.75–1.25 normal, > 1.25 active
Sensitivity	**$S_t = q_u$(undisturbed)/q_u(remoulded)** at the same w. 1 insensitive, 1–2 low, 2–4 medium, 4–8 sensitive, 8–16 extra-sensitive, **> 16 quick** (Skempton)

- **Thixotropy** is the regain of strength with time after remoulding, at constant water content. It is reversible.
- **Consistency** applies to fine-grained soils. **Relative density** applies to coarse-grained soils.

MEMORY TRICK

"**Se = wG**": read it as "**S**ee w**G**". For the indices, "**L**iquidity is measured from the **L**ower limit (PL); **C**onsistency is measured from the **C**eiling (LL)."

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Saturated soil, w = 30%, G = 2.7. What is e? → **0.81**.
- Porosity when e = 0.6? → **0.375**.
- Which clay mineral shows maximum swelling? → **Montmorillonite**.
- Loess is deposited by? → **Wind (aeolian)**.
- Sensitivity > 16 indicates? → **Quick clay**.
- Sum of liquidity index and consistency index? → **1**.

6.2 Classification & Compaction ★★★

Fraction (IS 1498:1970)	Size range
Boulder	> 300 mm
Cobble	80–300 mm
Gravel	**4.75–80 mm** (coarse 20–80, fine 4.75–20)
Sand	**0.075–4.75 mm** (coarse 2.0–4.75, medium 0.425–2.0, fine 0.075–0.425)
Silt	**0.002–0.075 mm**
Clay	**< 0.002 mm** (2 µm)

KEY FORMULAE – GRADATION & SEDIMENTATION

- Uniformity coefficient **$C_u = D_{60}/D_{10}$**. Coefficient of curvature (gradation) **$C_c = D_{30}^2/(D_{10}\cdot D_{60})$**
- Well-graded: **gravel C_u > 4, sand C_u > 6, and 1 ≤ C_c ≤ 3**. C_u = 1 means a perfectly uniform soil.
- D_{10} is the **effective size** (Hazen).
- Stokes' law: **$v = (\gamma_s - \gamma_w)D^2/(18\mu)$**. Valid for **0.2 mm to 0.0002 mm** particles.

- Sieve analysis: IS 2720 Part 4:1985 (wet/dry sieving). The 75 µm sieve divides coarse from fine soil.
- **Hydrometer / pipette analysis** is used for fines (< 75 µm). The dispersing agent is **sodium hexametaphosphate + sodium carbonate**. Hydrometer readings need **meniscus, temperature and dispersing-agent corrections**.
- Stokes' law assumes spherical particles, no interference between particles and laminar settling. Real clay particles are plate-shaped, so the result is an **equivalent diameter**.

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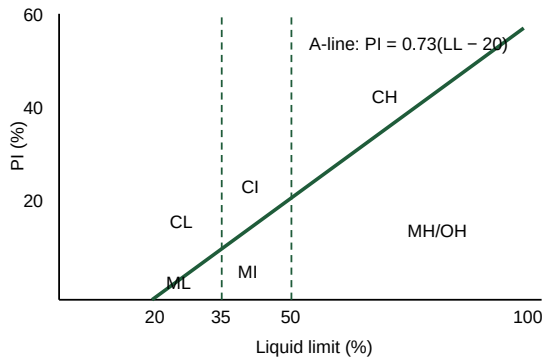

IS plasticity chart (IS 1498:1970). L: LL < 35, I: 35–50, H: LL > 50. Clays plot above the A-line and silts below it.

- **A-line: PI = 0.73(LL − 20). U-line** (upper limit for natural soils): PI = 0.9(LL − 8). Soils with PI 4–7 above the A-line fall in the hatched zone and get dual symbols such as **CL-ML**.
- **IS (1498)** has three plasticity ranges: L (< 35), **I (35–50)**, H (> 50). **USCS** has only two, L and H, divided at LL = 50.
- **Coarse-grained** soil has more than 50% retained on the 75 µm sieve. It is **gravel (G)** if more than half the coarse fraction is retained on 4.75 mm, otherwise **sand (S)**.
- Fines below 5% give GW/GP/SW/SP. Fines above 12% give GM/GC/SM/SC. Fines of 5–12% give dual symbols (e.g. SW-SM).
- Prefixes: G gravel, S sand, M silt (Swedish *mo*), C clay, O organic, **Pt peat**. Suffixes: W well graded, P poorly graded.
- **Field identification** of fines: **dilatancy** (silt reacts quickly, clay does not), **toughness** and **dry strength** (high for clay), feel (gritty silt, smooth clay).

Compaction test	Standard Proctor (IS 2720 Part 7:1980)	Modified Proctor (IS 2720 Part 8:1983)
Rammer mass	**2.6 kg**	**4.9 kg**
Height of drop	**310 mm**	**450 mm**
Layers × blows	**3 × 25**	**5 × 25**
Mould volume	1000 cm^3 (2250 cm^3 for coarse soil, 56 blows)	1000 cm^3 (2250 cm^3, 56 blows)
Energy	≈ **593 kJ/m^3** (≈ 6 kg·cm/cm^3)	≈ **2700 kJ/m^3**, ≈ **4.5 times** standard
Result	Lower MDD, higher OMC	**Higher MDD, lower OMC**

KEY FORMULAE – COMPACTION & CBR

- Zero air voids (100% saturation) line: $\gamma_d = G\gamma_w/(1 + wG)$. Every compaction curve lies below (to the left of) it.
- Relative compaction = $\gamma_{d,field}/\gamma_{d,max(lab)} \times 100$. Typically ≥ 95% is specified for embankments and subgrade.
- **CBR** = (test load ÷ standard load) × 100. Standard loads are **1370 kg at 2.5 mm** and **2055 kg at 5.0 mm** penetration. Normally the 2.5 mm value is reported. If the 5 mm value is higher, the test is repeated, and if it is still higher, the 5 mm value is adopted.

- Compaction removes **air**; consolidation removes **water** under sustained load.
- The OMC is roughly at the plastic limit for clays. Heavier soils (clays) have a higher OMC and lower MDD. Well-graded coarse soils give the highest MDD. A **higher compactive effort** raises MDD, lowers OMC and moves the peak towards the ZAV line.
- **Dry of optimum**: flocculated structure, higher permeability, higher strength, brittle, swells more on wetting. **Wet of optimum**: dispersed structure, low permeability, flexible, shrinks more and builds higher pore pressure. Clay cores of dams are compacted **slightly wet of OMC**.
- **CBR test** (IS 2720 Part 16:1987): plunger dia **50 mm**, penetration rate **1.25 mm/min**, **4 days soaking**, 2.5 kg surcharge weights. Used for flexible pavement design (IRC 37:2018).
- **Field density**: **core cutter** (IS 2720 Part 29:1975) for soft, fine-grained soils free of stones. **Sand replacement** (IS 2720 Part 28:1974) for gravelly or hard soils, using uniformly graded sand passing 600 µm and retained on 300 µm. Other methods: rubber balloon, water displacement, nuclear gauge. **Proctor needle** is used for field water content.

Field equipment	Best suited to
Sheepsfoot roller	**Clays / cohesive soils** (kneading, compacts from the bottom up)
Smooth-wheeled roller	Granular base courses, crushed rock, finishing the subgrade and asphalt
Pneumatic-tyred roller	Sandy silts, mixed soils (kneading plus static pressure)
Vibratory roller / plate	**Cohesionless** sands and gravels
Rammers / tampers	Confined areas, trenches, behind walls
Grid roller	Weathered rock, well-graded coarse soils

MEMORY TRICK

"**Sheep eat Clay, Vibes shake Sand**": a sheepsfoot roller for clay, a vibratory roller for sand. Proctor numbers: **2.6–310–3** (standard) and **4.9–450–5** (modified).

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- Equation of the A-line? → **PI = 0.73(LL − 20)**.
- Rammer mass and drop in standard Proctor? → **2.6 kg, 310 mm**.
- A sand is well graded if? → **C_u > 6 and 1 ≤ C_c ≤ 3**.
- Standard load at 2.5 mm penetration in CBR? → **1370 kg**.
- Field density of a stony soil is found by? → **Sand replacement method**.
- Silt size range as per IS? → **0.002–0.075 mm**.

6.3 Permeability & Seepage ★★★

KEY FORMULAE – PERMEABILITY

- Darcy's law: **v = k·i**, q = kiA. Valid only for **laminar flow** (Re < 1).
- Seepage velocity **v_s = v/n**, which is greater than the discharge velocity v.
- Constant head: **k = QL/(Aht)**. Falling head: **k = 2.303 (aL/At) $\log_{10}(h_1/h_2)$**
- Hazen: **k = C·D_{10}^2**, with k in cm/s, D_{10} in cm and C ≈ 100 (for clean sands)
- Kozeny–Carman: k ∝ $(\gamma_w/\mu)\cdot e^3/(1+e)\cdot D^2$. So k ∝ D^2, **k ∝ γ_w/μ** (k rises as temperature rises) and k ∝ $e^3/(1+e)$.
- Layered soil, flow parallel to layers: **$k_h = \Sigma k_i H_i/\Sigma H_i$**. Flow normal to layers: **$k_v = \Sigma H_i/\Sigma(H_i/k_i)$**. Always **$k_h > k_v$**.
- Pumping test, unconfined aquifer: **$k = q\ \ln(r_2/r_1)/[\pi(h_2^2 - h_1^2)]$**. Confined aquifer of thickness b: **$k = q\ \ln(r_2/r_1)/[2\pi b(h_2 - h_1)]$**

Soil	k (cm/s)	Drainage
Clean gravel	> 1 (10^0–10^2)	Very good
Clean sand	10^{-3}–1	Good
Fine sand, silty sand	10^{-5}–10^{-3}	Fair
Silt	10^{-7}–10^{-5}	Poor
Clay	**< 10^{-7}**	Practically impervious

- **Constant-head test** is for **coarse (pervious)** soils (IS 2720 Part 36:1987). **Falling (variable)-head test** is for **fine (less pervious)** soils (IS 2720 Part 17:1986). The **consolidation test** gives k of clays indirectly: $k = c_v m_v \gamma_w$.
- **Field tests**: pumping-out test (most reliable, gives an average k), pumping-in test, Lefranc test. The **Thiem** equation gives steady flow to wells.
- Two-dimensional steady seepage follows the **Laplace equation** $\partial^2h/\partial x^2 + \partial^2h/\partial z^2 = 0$. The assumptions are an isotropic and homogeneous soil, incompressible fluid and soil, and Darcy flow.
- **Flow net**: **flow lines** and **equipotential lines** intersect at **right angles** and form curvilinear squares. Uses: seepage discharge, uplift pressure, exit gradient and piping checks.
- For an anisotropic soil, scale the x-axis by $\sqrt{(k_z/k_x)}$ and use the equivalent permeability **$k' = \sqrt{(k_x k_z)}$**.
- Other ways to draw a flow net: **electrical analogy**, sand models, **graphical (trial sketching)**, and the Casagrande parabola for the phreatic line of an earth dam.

KEY FORMULAE – SEEPAGE

- Seepage per unit width: **q = kH·(N_f/N_d)**, where N_f = number of flow channels and N_d = number of equipotential drops. N_f/N_d is the **shape factor**.
- Critical hydraulic gradient: **$i_c = (G - 1)/(1 + e) = \gamma'/\gamma_w \approx 1.0$**
- Seepage pressure = $i\gamma_w z$. Seepage force per unit volume = **$i\gamma_w$**, acting in the direction of flow.
- Factor of safety against piping/boiling = i_c/i_{exit}. Adopt **3 to 4**.

- **Quick sand / boiling** is a **condition**, not a type of soil. It happens when **upward** seepage makes effective stress zero ($i \geq i_c$). It is most common in **fine sands and silts**: clays have cohesion, and gravels need flows too large to occur.
- **Piping** is progressive backward erosion starting at the exit (downstream toe). Prevent it with cut-offs, a longer seepage path, filters and an inverted filter at the exit.
- **Filter criteria (Terzaghi / USBR)**: **$D_{15(filter)}/D_{85(soil)} \leq 4$–5** (piping/retention criterion). **$D_{15(filter)}/D_{15(soil)} \geq 4$–5** (permeability criterion). $D_{50(f)}/D_{50(s)} \leq 25$. The filter grading curve should be roughly parallel to the soil's.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Permeability of a clay is best found by? → **Falling-head test** (or indirectly from consolidation).
- Flow lines and equipotential lines meet at? → **90°**.
- G = 2.67, e = 0.67. Find i_c. → **1.0**.
- For a stratified deposit, k_h vs k_v? → **$k_h > k_v$**.
- Darcy's law is valid for? → **Laminar flow**.

6.4 Effective Stress, Consolidation & Compressibility ★★★

- **Terzaghi's effective stress principle**: **σ′ = σ − u**. **Effective stress** controls shear strength and volume change. It is an abstract stress, not the true contact stress.
- Below the water table, σ′ = γ′z for a submerged soil. **Raising the water table lowers σ′**; lowering it (by pumping) raises σ′ and causes settlement.
- Upward seepage **reduces** σ′ by $i\gamma_w z$. Downward seepage **increases** it.
- **Capillary zone**: the pore pressure is **negative** (suction), so σ′ increases. Capillary rise **$h_c = 4T\cos\alpha/(\gamma_w d)$**, about **0.3/d cm** (d in cm) for water. Hazen: $h_c = C/(eD_{10})$, C = 0.1–0.5 cm^2. Capillary rise is largest in **clays** and smallest in gravels.

Terzaghi 1-D consolidation – assumptions
Soil is **homogeneous and fully saturated**; soil grains and water are **incompressible**

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Drainage and compression are **one-dimensional (vertical)**; Darcy's law is valid
k and m_v remain constant during consolidation; strains are small
Delay in compression is due **only to permeability** (secondary compression is ignored)

KEY FORMULAE – CONSOLIDATION

- Coefficient of compressibility $a_v = -\Delta e/\Delta\sigma'$. Coefficient of volume change $\mathbf{m_v = a_v/(1 + e_0)}$
- Compression index $\mathbf{C_c = \Delta e/\log(\sigma_2'/\sigma_1')}$. Skempton: $\mathbf{C_c = 0.009(LL - 10)}$ for undisturbed clay and $\mathbf{0.007(LL - 7)}$ for remoulded clay. Swelling/recompression index $C_s \approx$ (1/5 to 1/10)C_c.
- Coefficient of consolidation $\mathbf{c_v = k/(m_v\gamma_w)}$ (units m^2/s or cm^2/s). Time factor $\mathbf{T_v = c_vt/d^2}$, where d = drainage path (**H/2 for double drainage**, H for single drainage).
- $T_v = (\pi/4)U^2$ for U ≤ 60%. $T_v = 1.781 - 0.933 \log_{10}(100 - U\%)$ for U > 60%.
- $\mathbf{T_{50} = 0.197}$, $\mathbf{T_{60} = 0.287}$, $\mathbf{T_{90} = 0.848}$
- Primary settlement of an NC clay: $\mathbf{S_c = [C_cH/(1 + e_0)] \log_{10}[(\sigma_0' + \Delta\sigma)/\sigma_0']}$. Alternatively $S_c = m_vH\Delta\sigma = H\Delta e/(1 + e_0)$.
- OC clay with $\sigma_0' + \Delta\sigma \le \sigma_c'$: use C_s in place of C_c. If the final stress exceeds σ_c', add a C_s part up to σ_c' and a C_c part beyond it.
- Secondary compression: $\mathbf{S_s = [C_\alpha H/(1 + e_p)] \log(t_2/t_1)}$. $C_\alpha/C_c \approx 0.04 \pm 0.01$ for inorganic clays.
- Time for the same degree of consolidation: $\mathbf{t \propto d^2}$. Changing from single to double drainage cuts time to ¼.

Method (oedometer, IS 2720 Part 15:1986)	Plot	Gives	Key construction
Taylor	Dial reading vs **√t**	t_{90}, $c_v = 0.848d^2/t_{90}$	Draw a second line with abscissae **1.15 times** those of the initial straight line
Casagrande	Dial reading vs **log t**	t_{50}, $c_v = 0.197d^2/t_{50}$	d_0 from the **1:4 time ratio**; d_{100} from the intersection of tangents

- **Pre-consolidation pressure σ_c'** is the maximum effective stress the soil has carried in the past. It is found by the **Casagrande construction** on the e–log σ′ curve, at the point of maximum curvature.
- **OCR = σ_c'/σ_0'. NC clay**: OCR = 1. **OC clay**: OCR > 1 (caused by erosion, a falling water table, desiccation or ice sheets). **Under-consolidated**: OCR < 1 (recent fill, still consolidating).
- Compared with NC clays, OC clays have lower compressibility, higher strength, dilate in shear and develop negative pore pressure.
- **Primary consolidation** is the expulsion of pore water, i.e. dissipation of excess pore pressure. **Secondary compression** is plastic readjustment of particles (creep) at constant σ′ and is significant in **organic soils and peat**.
- **Immediate (elastic) settlement** happens without drainage. It dominates in sands. In sands, consolidation settlement is negligible and quick.
- Total settlement $S = S_i + S_c + S_s$. Elastic settlement $S_i = qB(1 - \mu^2)I_f/E$.
- **Spring analogy** (Terzaghi): the spring is the soil skeleton, the water is pore water and the valve opening is permeability. At t = 0, the whole load is carried by water.

MEMORY TRICK

"**Taylor Root, Casagrande Log**": TR-CL. "**Fifty is point one-nine-seven, ninety is point eight-four-eight.**" Taylor uses 90 and 1.15; Casagrande uses 50 and 1:4.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Time factor for 50% consolidation? → **0.197**.
- Taylor's method gives? → $\mathbf{t_{90}}$ (square-root-of-time fitting).
- Skempton's C_c for undisturbed clay with LL = 50? → **0.36**.
- A clay layer is changed from single to double drainage. The time for the same U becomes? → **One-fourth**.
- Effective stress in the capillary zone (compared with no capillarity)? → **Increases** (pore pressure is negative).
- OCR of a normally consolidated clay? → **1**.

6.5 Shear Strength & Stress Distribution ★★★

KEY FORMULAE – SHEAR STRENGTH

- Mohr–Coulomb: $\mathbf{\tau_f = c + \sigma \tan\varphi}$. In effective stress terms: $\mathbf{\tau_f = c' + \sigma' \tan\varphi'}$.
- The failure plane is inclined at $\mathbf{\theta = 45° + \varphi/2}$ to the **major principal plane**.
- $\mathbf{\sigma_1 = \sigma_3 \tan^2(45° + \varphi/2) + 2c \tan(45° + \varphi/2)}$
- Unconfined compression ($\sigma_3 = 0$, $\varphi = 0$): $\mathbf{q_u = 2c_u}$, so $c_u = q_u/2$.
- Vane shear, both ends shearing: $\mathbf{\tau = T/[\pi D^2(H/2 + D/6)]}$. With H = 2D this becomes $\tau = T/(3.67D^3)$.
- Skempton pore pressure: $\mathbf{\Delta u = B[\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)]}$. B = 1 for a saturated soil and B = 0 for a dry soil.
- Maximum shear stress = $(\sigma_1 - \sigma_3)/2$ on a 45° plane. It is not the failure plane unless $\varphi = 0$.

Test	IS 2720	Key facts
Direct shear (box)	Part 13:1986	Box 60 × 60 mm. Failure plane is **predetermined** (horizontal), stress distribution is non-uniform and drainage cannot be controlled. Good for **sands**.

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Triaxial UU	Part 11:1993	Quick test. $\varphi_u = 0$ for saturated clay. Used for **end-of-construction** stability on clay.
Triaxial CU (with u measured)	Part 12:1981	Gives c′ and φ′ plus c_{cu} and φ_{cu}. Used for **sudden drawdown** and staged loading.
Triaxial CD	Part 12:1981	Slow test giving c′, φ′. Used for **long-term stability** (e.g. steady seepage, cuts in clay).
Unconfined compression	Part 10:1991	Special triaxial test with $\sigma_3 = 0$. For **saturated clays** only, not for sands. Specimen L/D = 2.
Vane shear	Part 30:1980	**In-situ** undrained strength of **soft, sensitive clays**. H/D = 2.

- In the triaxial test, the **specimen length is 2 to 2.5 times** its diameter (commonly 38 mm × 76 mm). **Deviator stress** = $\sigma_1 - \sigma_3$. All drainage conditions can be controlled and pore pressure can be measured. This is the main advantage of the triaxial test.
- **Dense sand** shows a peak and then strain softening, dilates and has negative Δu (undrained). **Loose sand** has no peak, contracts and has positive Δu. The void ratio at which volume does not change is the **critical void ratio**.
- Typical $\mathbf{A_f}$ values: NC clay 0.5–1.0, **highly sensitive clay > 1**, lightly OC 0–0.5, **heavily OC −0.5 to 0**.
- Typical φ for sand: loose ≈ 28–30°, dense ≈ 35–45°. Angular, well-graded and dense sand gives a higher φ.

KEY FORMULAE – STRESS DISTRIBUTION

- Boussinesq, point load: $\boldsymbol{\sigma_z = (3Q/2\pi z^2)\cdot[1/(1 + (r/z)^2)]^{5/2} = I_B \cdot Q/z^2}$. Directly below the load (r = 0), $\mathbf{I_B = 3/2\pi = 0.4775}$.
- Westergaard (μ = 0): $\boldsymbol{\sigma_z = (Q/\pi z^2)\cdot[1/(1 + 2(r/z)^2)]^{3/2}}$. At r = 0, $\mathbf{I_W = 1/\pi = 0.3183}$, about ⅔ of the Boussinesq value.
- Line load: $\sigma_z = (2q/\pi z)\cdot[1/(1 + (x/z)^2)]^2$. Below a uniformly loaded circular area at the centre: $\sigma_z = q[1 - \{1/(1 + (R/z)^2)\}^{3/2}]$.
- **2:1 (approximate) method**: $\boldsymbol{\sigma_z = Q/[(B + z)(L + z)]}$. For a strip, $\sigma_z = qB/(B + z)$.
- Rectangular area, corner method (Steinbrenner/Fadum): $\sigma_z = q\cdot I_\sigma(m, n)$ with m = B/z, n = L/z. For a point inside, add the four rectangles; for a point outside, add and subtract.

Theory	Soil assumption	Use
Boussinesq (1885)	Semi-infinite, **homogeneous, isotropic**, linearly elastic; stress is independent of E and μ	Homogeneous soils (clays). Gives larger stresses, so it is conservative.
Westergaard (1938)	Elastic medium with thin **rigid horizontal sheets** that prevent lateral strain	**Stratified/varved** soils

- **Pressure bulb** is an isobar, a contour of equal vertical stress. The zone inside the **0.1q–0.2q** isobar is the **significant depth**. It is about **1.5B–2B for square footings** and about **3B–4B for strip footings**.
- **Newmark's influence chart** is based on Boussinesq. It has 10 circles × 20 sectors = **200 units**, so the **influence value is 1/200 = 0.005**. $\sigma_z = 0.005 \times N \times q$. The scale line AB on the chart equals the depth z. The chart can be used for any shape of loaded area.

MEMORY TRICK

"**Bous = 0.48, West = 0.32**": Boussinesq is about 1.5 times Westergaard below the load. "**Newmark 200 → 0.005**."

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Failure plane angle with the major principal plane? → **45° + φ/2**.
- Unconfined compressive strength of a clay is 100 kPa. Cohesion? → **50 kPa**.
- Boussinesq influence factor directly below a point load? → **0.4775**.
- Influence value of a standard Newmark chart? → **0.005**.
- Best test for in-situ strength of soft sensitive clay? → **Vane shear test**.
- Skempton's B for a fully saturated soil? → **1**.

6.6 Earth Pressure & Slope Stability ★★☆

State	Wall movement	Coefficient (cohesionless, Rankine)	Typical (φ = 30°)
At rest	None (e.g. basement walls, bridge abutments with rigid restraint)	$\mathbf{K_0 = 1 - \sin\varphi'}$ (Jaky); = μ/(1 − μ) (elastic)	0.5
Active	**Away** from the backfill (very small movement is enough)	$\mathbf{K_a = (1 - \sin\varphi)/(1 + \sin\varphi) = \tan^2(45° - \varphi/2)}$	**1/3**
Passive	**Towards** the backfill (much larger movement needed)	$\mathbf{K_p = (1 + \sin\varphi)/(1 - \sin\varphi) = 1/K_a}$	**3**

- The order is always $\mathbf{K_a < K_0 < K_p}$.
- The active state needs a wall movement of only about 0.1–0.5% of H. The passive state needs about 1–5% of H.
- The Rankine failure plane is at **45° + φ/2** to the horizontal in the active case and **45° − φ/2** in the passive case.

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KEY FORMULAE – EARTH PRESSURE

- Dry cohesionless backfill: $\mathbf{P_a = \tfrac{1}{2}K_a\gamma H^2}$ acting at **H/3** above the base.
- Uniform surcharge q gives an extra uniform pressure $\mathbf{K_aq}$, so the extra force K_aqH acts at H/2.
- Submerged backfill: $p = K_a\gamma' z + \gamma_w z$. Water pressure is added in full (K = 1 for water).
- Cohesive soil (active): $\mathbf{p_a = K_a\gamma z - 2c\sqrt{K_a}}$. Passive: $p_p = K_p\gamma z + 2c\sqrt{K_p}$.
- Depth of tension crack: $\mathbf{z_c = 2c/(\gamma\sqrt{K_a})}$. For $\varphi = 0$, $z_c = \mathbf{2c/\gamma}$.
- Critical height of an unsupported vertical cut: $\mathbf{H_c = 2z_c = 4c/(\gamma\sqrt{K_a})}$, or $\mathbf{4c/\gamma}$ for $\varphi = 0$. Taylor's value is $3.85c/\gamma$.
- Inclined cohesionless backfill (angle β): $K_a = \cos\beta\cdot[\cos\beta - \sqrt{(\cos^2\beta - \cos^2\varphi)}]/[\cos\beta + \sqrt{(\cos^2\beta - \cos^2\varphi)}]$. The pressure acts parallel to the backfill surface.

Rankine (1857)	Coulomb (1776) wedge theory
Wall is **smooth** and vertical; analyses a state of stress (plastic equilibrium)	Includes **wall friction δ** and a battered wall; analyses the equilibrium of a **sliding wedge** with a plane failure surface
Active pressure slightly **over-estimated** and passive **under-estimated**, so it is conservative	Good for active pressure. **Over-estimates passive** pressure when $\delta > \varphi/3$.
Resultant is parallel to the backfill surface	Resultant is inclined at δ to the wall normal. Graphical solutions: **Rebhann**, **Culmann**, trial wedge.

- **Retaining wall checks**: overturning, sliding, bearing pressure (no tension at the base, resultant in the **middle third**, e ≤ B/6), and overall (deep-seated) stability.
- IS 456:2000 cl. 20: restoring moment ≥ **1.2 × overturning moment due to dead load + 1.4 × that due to imposed load**, and factor of safety against sliding ≥ **1.4** (only 0.9 × dead load counted where it resists). Textbooks often use **2.0 for overturning and 1.5 for sliding**.
- Drainage behind the wall: **weep holes** (about 75–100 mm, spaced 1–2 m) with a filter. Adding water behind a wall roughly doubles the thrust, so drainage is essential.
- Wall types: gravity, semi-gravity, **cantilever** (economical up to about 6 m), **counterfort** (more than about 6–7 m; counterforts are on the backfill side), buttress (on the front side), crib, gabion, reinforced earth.

KEY FORMULAE – SLOPE STABILITY

- Infinite slope, dry cohesionless soil: $\mathbf{F = \tan\varphi/\tan\beta}$. Stable up to $\beta = \varphi$.
- Infinite slope with seepage parallel to the surface (saturated): $\mathbf{F = (\gamma'/\gamma_{sat})\cdot\tan\varphi/\tan\beta}$, about half the dry value.
- Infinite slope in c–φ soil, critical depth: $H_c = c/[\gamma\cos^2\beta(\tan\beta - \tan\varphi)]$.
- Swedish circle ($\varphi = 0$): $\mathbf{F = c_u\cdot L_{arc}\cdot r/(W\cdot\bar{x})}$
- Taylor's stability number: $\mathbf{S_n = c/(F_c\gamma H)}$. For a vertical cut with $\varphi = 0$, $S_n = 0.261$, so $H_c = 3.85c/\gamma$. For $\varphi = 0$ and slopes flatter than about 53° on deep clay, $S_n = \mathbf{0.181}$ (base failure).
- Fellenius (ordinary) method of slices: $F = [\Sigma c'l + \Sigma(W\cos\alpha - ul)\tan\varphi']/\Sigma W\sin\alpha$. **Bishop's simplified** method is more accurate. The ordinary method is conservative by about 5–20%.

- **FOS definitions**: with respect to shear strength, $F_s = \tau_f/\tau_{mobilised}$; with respect to cohesion, F_c (φ fully mobilised); with respect to friction, F_φ. When $F_c = F_\varphi$, both equal F_s.
- Failure circles: **toe failure** (steep slopes, φ > about 3°), **slope (face) failure**, and **base failure** (soft clay with a hard stratum deep below; the midpoint circle passes below the toe).
- Fellenius gives direction angles for locating the centre of the critical circle when $\varphi = 0$. The **friction circle method** (Taylor) handles c–φ soils with radius r sin φ.
- Critical conditions for earth dams: **upstream slope during sudden drawdown**, **downstream slope during steady seepage** with the reservoir full, and both slopes at **end of construction**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Rankine K_a for $\varphi = 30°$? → **1/3**.
- Depth of tension crack in clay ($\varphi = 0$)? → **2c/γ**.
- Rankine's theory assumes the wall back is? → **Smooth and vertical**.
- Most critical condition for the upstream slope of an earth dam? → **Sudden drawdown**.
- FOS of a dry infinite sand slope? → **tan φ/tan β**.

6.7 Shallow Foundations & Bearing Capacity ★★★

- **Shallow foundation**: $D_f \le B$ (Terzaghi). Types: **isolated/spread** footing, **combined** footing (rectangular or trapezoidal), **strap (cantilever)** footing, **strip/wall** footing, **raft/mat**.
- A **trapezoidal combined footing** is used when the heavier column is near the property line or space is restricted. A **strap footing** is used when an exterior column is at the boundary and the columns are far apart.

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- A **raft** is chosen when the required footing area exceeds **50%** of the plan area, or to reduce differential settlement on erratic soil. A **floating (compensated) raft** has net pressure close to zero because the excavated soil weight equals the building load.
- **Minimum depth** of foundation as per IS 1904 is **0.5 m**. In black cotton soil, go below the zone of seasonal moisture variation, about 1.5–3.5 m.

KEY FORMULAE – BEARING CAPACITY

- Rankine's minimum depth: $\mathbf{D_f = (q/\gamma)\cdot[(1 - \sin\varphi)/(1 + \sin\varphi)]^2 = (q/\gamma)K_a^2}$
- Terzaghi, strip footing (general shear): $\mathbf{q_u = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma}$
- Square footing: $\mathbf{q_u = 1.3cN_c + \gamma D_f N_q + 0.4\gamma B N_\gamma}$
- Circular footing (B = diameter): $\mathbf{q_u = 1.3cN_c + \gamma D_f N_q + 0.3\gamma B N_\gamma}$
- Net ultimate: $\mathbf{q_{nu} = q_u - \gamma D_f}$. Net safe: $q_{ns} = q_{nu}/F$ (F = 2.5–3). Safe: $\mathbf{q_s = q_{nu}/F + \gamma D_f}$.
- Local shear (Terzaghi): use $\mathbf{c_m = \tfrac{2}{3}c}$ and $\mathbf{\tan\varphi_m = \tfrac{2}{3}\tan\varphi}$, with N'_c, N'_q, N'_γ.
- Pure clay ($\varphi = 0$): Terzaghi gives $\mathbf{N_c = 5.7}$, $N_q = 1$, $N_\gamma = 0$. Prandtl/Skempton/IS give $\mathbf{N_c = 5.14\ (\pi + 2)}$. Skempton for a square/circular footing on the surface gives 6.2.
- IS 6403:1981 (Vesic factors): $N_q = e^{\pi \tan\varphi}\tan^2(45° + \varphi/2)$; $N_c = (N_q - 1)\cot\varphi$; $N_\gamma = 2(N_q + 1)\tan\varphi$. For $\varphi = 30°$: $\mathbf{N_c = 30.14,\ N_q = 18.40,\ N_\gamma = 22.40}$.
- IS 6403 shape factors (rectangle): $s_c = s_q = 1 + 0.2B/L$, $s_\gamma = 1 - 0.4B/L$. Square/circle: $s_c = s_q = 1.3$, $s_\gamma = 0.8$ (circle 0.6). Inclination: $i_c = i_q = (1 - \alpha/90)^2$, $i_\gamma = (1 - \alpha/\varphi)^2$.

Term	Definition
Ultimate bearing capacity q_u	Gross pressure at the base at which the soil fails in shear
Net ultimate q_{nu}	q_u minus overburden pressure γD_f
Net safe q_{ns}	q_{nu}/FOS, considering **shear failure only**
Allowable bearing pressure	The **lesser** of the net safe bearing capacity (shear) and the **safe bearing pressure for permissible settlement**

Failure mode (Vesic)	Soil	Features
General shear	Dense sand (I_D > 70%), stiff clay; **φ > 36°**	Well-defined failure surface reaching the ground, **heaving** on the sides, clear peak in the load–settlement curve, sudden tilting
Local shear	Medium dense sand, **φ < 29°**	Failure surface does not reach the surface, slight heave, no clear peak
Punching shear	Loose sand, soft clay, deep footings	Vertical shear around the footing edge, **no heave**, large settlement

- IS 6403: use general shear for $\varphi \geq 36°$ and local shear for $\varphi \leq 29°$, and interpolate between them.
- **Water table correction** (IS 6403, W′ factor on the N_γ term): **W′ = 0.5** when the water table is at or above the base. **W′ = 1** when it is at depth ≥ B below the base. Interpolate linearly between these. A water table at ground level roughly **halves** both the N_q and N_γ terms in sand.
- Eccentric load: use the **effective width B′ = B − 2e** (Meyerhof).

Plate load test (IS 1888:1982)	Value
Plate size	**300 mm** square minimum (also 450, 600, 750 mm); thickness ≥ 25 mm
Pit width	≥ **5 B_p**
Seating load	**7 kPa (70 g/cm²)**, released before the test
Load increment	About 1/5 of the expected safe load (or 1/10 of the ultimate)
Next increment applied when	Settlement rate < **0.02 mm/min** (minimum 1 h per stage)
Settlement, sand	$\mathbf{S_f = S_p[B_f(B_p + 0.3)/B_p(B_f + 0.3)]^2}$ (B in m)
Settlement, clay	$\mathbf{S_f = S_p\cdot B_f/B_p}$
Bearing capacity	Clay: $q_f = q_p$ (independent of size). Sand: $\mathbf{q_f = q_p\cdot B_f/B_p}$
Limitation	Influences only about 1.5–2B_p depth; short duration (no consolidation); scale effect

SPT (IS 2131:1981)	Value
Hammer / drop	**63.5 kg / 750 mm**
Split-spoon sampler	OD **50.8 mm**, ID 35 mm (area ratio ≈ 110%, so samples are **disturbed**)
N value	Blows for the last **300 mm** after **150 mm seating** drive (total drive 450 mm)
Refusal	50 blows for any 150 mm increment, or 100 blows for 300 mm, or 10 successive blows with no advance
Overburden correction	$N_c = C_N\cdot N$, $C_N = 0.77\log_{10}(2000/\sigma')$ with σ′ in kPa (Peck) or the IS 2131 chart
Dilatancy correction	Submerged fine sand/silt with N′ > 15: **N = 15 + ½(N′ − 15)**. Apply it after the overburden correction.

N (sand)	Density	N (clay)	Consistency
0–4	Very loose	< 2	Very soft
4–10	Loose	2–4	Soft
10–30	Medium	4–8	Medium
30–50	Dense	8–15	Stiff
> 50	Very dense	15–30 / > 30	Very stiff / Hard

- Other in-situ tests: **static cone penetration (Dutch cone)**, IS 4968 (Part 3):1976, with a cone of 60° apex and 10 cm² base area. It is best for soft clays and silts and gives point resistance q_c and sleeve friction. The **dynamic cone** test is

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IS 4968 (Parts 1 & 2). The pressuremeter measures lateral deformation.

IS 1904:1986 permissible settlement (RCC structures)	Sand & hard clay	Plastic clay
Isolated foundation – maximum settlement	**50 mm**	**75 mm**
Isolated – angular distortion	1/666	1/666
Raft foundation – maximum settlement	**75 mm**	**100 mm**
Raft – angular distortion	1/500	1/500

- For steel structures on isolated foundations, IS 1904 allows 50 mm with angular distortion 1/300. Terzaghi–Peck's older limits for sand are **25 mm (isolated)** and 50 mm (raft).
- **Differential settlement** causes cracking, not total settlement. Angular distortion = differential settlement ÷ column spacing. Bjerrum: about **1/150** means structural damage likely, and 1/300 is the first cracking in panel walls.

CODE UPDATE

IS 1904 was revised in 2021 (combining general requirements for foundations). Exam questions still quote the IS 1904:1986 settlement table (50/75 mm isolated, 75/100 mm raft). Bearing capacity is IS 6403:1981, plate load test is IS 1888:1982, and SPT is IS 2131:1981.

MEMORY TRICK

Terzaghi shape factors "**1.3 – 0.4 Square, 1.3 – 0.3 Circle, 1.0 – 0.5 Strip**": the γ factor **drops by 0.1** going strip → square → circle. SPT: "**63.5 – 750 – 150 – 300**".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Terzaghi's N_c for φ = 0? → **5.7**.
- Bearing capacity of a square footing on sand is? → **$1.3cN_c + qN_q + 0.4\gamma BN_\gamma$**.
- Minimum plate size in a plate load test? → **300 mm**.
- SPT hammer weight and drop? → **63.5 kg, 750 mm**.
- Water table at the base of a footing on sand reduces the N_γ term by? → **50%**.
- Permissible maximum settlement of an isolated footing on clay (IS 1904)? → **75 mm**.

6.8 Deep Foundations ★★★

Basis	Types
Load transfer	**End-bearing** (point) piles rest on a hard stratum. **Friction** piles carry load by skin friction in deep soft soil. **Compaction** piles densify loose sand. Also tension (uplift) piles, anchor piles, batter piles (lateral loads), sheet piles (retaining).
Material	Timber, concrete (precast/cast-in-situ), steel (H-pile, pipe), composite
Installation	**Driven** (displacement; densifies sand), **bored** (non-displacement), driven cast-in-situ, **bored cast-in-situ**, **under-reamed**

- Pile codes: IS 2911 (Part 1/Sec 1):2010 driven cast-in-situ; (Part 1/Sec 2):2010 **bored cast-in-situ**; (Part 1/Sec 3):2010 driven precast; (Part 1/Sec 4):2010 precast in bored holes; **(Part 3):1980 under-reamed piles**; (Part 4):2013 load tests.
- **Under-reamed piles** (IS 2911 Part 3) are bored cast-in-situ piles with enlarged bulbs. They are used in **expansive (black cotton) soils**, where they anchor against uplift, and in loose fills.
- Under-reamed pile details:
  - Bulb diameter **$D_u = 2.5D$** (normally 2–3D).
  - Vertical spacing of bulbs: **1.25 to 1.5 D_u**.
  - Minimum pile length **3.5 m**.
  - Pile spacing ≥ **$2D_u$**.
  - Top bulb at least $2D_u$ (and not less than 1.75 m) below ground level.
  - A double under-reamed pile carries about **1.5 times** the load of a single under-reamed pile.
- **Minimum pile spacing** (IS 2911): **2.5D** for end-bearing piles and **3D** for friction piles. Spacing is usually 2.5–3.5D. Too close causes overlap of stress zones and heave; too wide makes a costly pile cap.

KEY FORMULAE – PILE CAPACITY

- Static formula: **$Q_u = Q_b + Q_s = q_bA_b + f_sA_s$**. In clay: Q_b = **$9c_uA_b$** (N_c = 9) and Q_s = **$\alpha\bar{c}A_s$**, where α is the adhesion factor (≈ 0.3–1.0, lower for stiff clay). In sand: $q_b = \sigma'_vN_q$, $f_s = K\sigma'_v \tan\delta$, with σ'_v limited below the critical depth (≈ 15–20D).
- **Engineering News Record** (ENR): **$Q_a = WH/[6(S + C)]$**. Q_a in kg, W in kg, H and S in cm, FOS = **6**. C = **2.5 cm** for a drop hammer and **0.25 cm** for single/double-acting steam hammers. S = average penetration per blow over the last 5 blows (drop hammer) or 20 blows (steam).
- **Hiley**: $Q_u = \eta_h WH{\cdot}\eta_b/(S + C/2)$, where $C = C_1 + C_2 + C_3$ are temporary elastic compressions of the pile cap, pile and soil, and η_b is the efficiency of the blow. IS 2911 includes this as the modified Hiley formula.
- **Converse–Labarre** group efficiency: **$\eta_g = 1 - \theta[(n - 1)m + (m - 1)n]/(90mn)$**, with $\theta = \tan^{-1}(d/s)$ in degrees, m rows and n piles per row.
- Group in clay: Q_g = the **lesser** of $(n{\cdot}Q_{single})$ and the block failure load $(c_uN_cB_gL_g + 2(B_g + L_g)L{\cdot}\bar{c}_u)$. The group settles more than a single pile.
- **Negative skin friction** in clay fill: Q_{nf} = perimeter × L_{fill} × c_u (or αc_u). It **adds load** to the pile and is **not** counted as capacity.

- **Dynamic formulas** are not reliable for clays: driving remoulds the clay and builds pore pressure. They suit **cohesionless soils**. **Feld's rule**: reduce each pile's capacity by 1/16 for each adjacent pile (diagonal or straight).

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- For driven piles in loose sand, group efficiency may be **> 1** because driving densifies the sand. For friction piles in clay, $\eta_g < 1$.
- **Negative skin friction (down-drag)** happens when soil around the pile settles more than the pile. Causes: recent fill consolidating, lowering of the water table, soft clay under surcharge. The **neutral plane** is where there is no relative movement. Remedies: bitumen coating, casing/sleeve, pre-loading the fill.

Pile load test (IS 2911 Part 4:2013)	Key facts
Initial test	On a test pile (not used in the works) loaded to at least **2.5 × the estimated safe load** (or failure). Safe load = **lesser of ⅔ of the load at 12 mm total settlement** and **50% of the load at settlement = 10% of pile diameter** (7.5% for under-reamed).
Routine test	On working piles (about 0.5–2% of piles), loaded to **1.5 × working load**. Total settlement should not exceed 12 mm.
Cyclic load test	**Separates skin friction and end bearing** (loading–unloading cycles)
Other tests	Lateral load test, pull-out (uplift) test, pile integrity test (low strain), high-strain dynamic test (PDA)

- **Well foundations** are used for bridge piers and abutments in rivers with deep scour (IRC 78:2014, IS 3955:1967).
  - Components, from the bottom up: **cutting edge** (steel, about 30–40° to the vertical), **well curb** (RCC, wedge-shaped), **steining** (the main wall, which sinks the well by its weight), **bottom plug** (concrete placed underwater by tremie), **sand filling** (optional), **top plug**, **well cap**.
  - Shapes: **circular** (most common, easy to sink, least tilting), dumb-bell, **double-D**, twin-circular, rectangular, double-octagonal.
  - Permissible **tilt 1 in 80** and **shift 150 mm** (IRC 78).
  - Tilt correction: eccentric kentledge, excavating more on the higher side, water/air jetting on the higher side, struts, pulling.
  - Grip length (depth below the maximum scour level) ≥ **⅓ of maximum scour depth**. Maximum scour depth is about $\mathbf{2d_{sm}}$ at **piers** and $1.27d_{sm}$ at abutments, where Lacey's $d_{sm} = 1.34(q^2/f)^{1/3}$.
  - Sinking aids: sand island (in water), kentledge, water jetting, blasting, dewatering, bentonite lubrication.
- **Caissons**:
  - **Open caisson** = well; open at top and bottom.
  - **Box caisson**: closed at the bottom, floated and sunk on a prepared bed.
  - **Pneumatic caisson**: a working chamber at the bottom under compressed air, which allows dry working. It is limited to about **35–40 m** below water (air pressure about 3.5–4 bar), and workers risk **caisson disease (the bends)**.

MEMORY TRICK

"**Well: 80–150**": tilt 1 in **80**, shift **150** mm. "**ENR 6 – 2.5 – 0.25**": FOS 6, drop hammer C = 2.5 cm, steam C = 0.25 cm. Under-reamed: "**2.5D bulb, 1.25–1.5 spacing, 3.5 m length**."

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Bulb diameter of an under-reamed pile? → **2.5 times the shaft diameter**.
- FOS in the Engineering News formula? → **6**.
- Pile group efficiency formula commonly used? → **Converse–Labarre**.
- Permissible tilt of a well foundation? → **1 in 80**.
- Test used to separate skin friction and end bearing? → **Cyclic pile load test**.
- Negative skin friction acts? → **Downward, increasing the load on the pile**.

6.9 Soil Exploration & Soil Improvement Techniques ★★★

Exploration method	Suitability / remarks
Test pits / trial pits	Shallow (≤ 3 m). Allows visual inspection and gives **undisturbed block samples**. The most reliable method but costly at depth.
Auger boring	Hand or power auger in soft to stiff cohesive soils above the water table. Samples are **disturbed**.
Wash boring	Water jet; quick and cheap. Sample is wash-water slurry (highly disturbed), but shows **changes of strata**. Not suited to gravels or boulders.
Percussion drilling	Heavy chisel. For **gravel, boulders**, hard strata.
Rotary drilling	For **rock** and all soils. Gives **rock cores** (core recovery, RQD). Uses bentonite mud.

- Planning code: **IS 1892:1979** (subsurface investigation). Undisturbed sampling: IS 2132:1986 (thin-walled tubes).
- **Depth of exploration**: down to where the added vertical stress is less than about 10% of the applied stress (or 10–20% of the effective overburden). Rule of thumb: **1.5 × width** for isolated footings. For pile groups, go at least 1.5 × group width below the pile tips. For rock, prove at least 3 m into rock.
- **Spacing** (IS 1892): for a compact building site of about **0.4 ha**, one borehole or pit at **each corner + one at the centre**. For large areas, about 30–50 m grid. For roads and canals, about 300–500 m along the alignment.
- **RQD = Σ lengths of core pieces ≥ 100 mm ÷ total run × 100**. < 25% very poor, 25–50 poor, 50–75 fair, 75–90 good, 90–100 excellent. Core recovery ratio = length of core ÷ length drilled.

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KEY FORMULAE – SAMPLERS

- Symbols: D_1 = inner diameter of the cutting edge, D_2 = outer diameter of the cutting edge, D_3 = inner diameter of the tube, D_4 = outer diameter of the tube.
- Area ratio $\mathbf{A_r = (D_2^2 - D_1^2)/D_1^2 \times 100}$. Must be **≤ 10%** for undisturbed samples (soft sensitive clays). Up to about 20% is acceptable in stiff clays. The SPT split spoon has A_r ≈ 110%.
- Inside clearance $\mathbf{C_i = (D_3 - D_1)/D_1 \times 100 = 1–3\%}$. This reduces wall friction on the sample entering the tube and allows elastic expansion.
- Outside clearance $\mathbf{C_o = (D_2 - D_4)/D_4 \times 100 = 0–2\%}$. This reduces the driving force when the tube is withdrawn.
- Recovery ratio L_r = L (sample length)/H (penetration). A value of about 0.96–0.98 is satisfactory. More than 1 means the sample has swelled.

- **Samplers**:
  - Open drive: thin-walled **Shelby tube**, low A_r.
  - Split spoon (SPT).
  - **Piston sampler**: for very soft and sensitive clays and sands below the water table.
  - Denison and Pitcher samplers: for stiff/hard soils, double tube.
  - Scraper bucket: for soils containing pebbles.
  - Core barrels (single, double, triple tube): for rock.
- **Geophysical methods**:
  - **Seismic refraction** uses seismic wave velocity. It works only if **velocity increases with depth**; a softer layer under a stiffer one is missed (**hidden layer**). Wave velocity is high in rock and saturated soil.
  - **Electrical resistivity** uses the **Wenner** arrangement (4 equally spaced electrodes, **ρ = 2πaR**) or the Schlumberger arrangement. Resistivity is **low in clay and saline water** and high in dry sand, gravel and rock. Used to find the water table, gravel deposits and depth to bedrock.
  - Others: ground-penetrating radar (GPR), cross-hole and down-hole seismic tests (dynamic moduli), and **SASW/MASW** (shear-wave velocity profiling).

Ground improvement technique	Suitable soil	Principle / facts
Vibroflotation (vibro-compaction)	**Loose cohesionless sand** (fines < about 10–15%)	Vibrating probe with water jets densifies sand in depth. Backfilled with sand or gravel.
Dynamic compaction (Ménard)	Granular fills, loose sands, rubble	Tamper of 10–40 t dropped 10–40 m. Depth of influence **D ≈ n√(WH)** (n ≈ 0.3–0.8, commonly 0.5; W in t, H in m).
Preloading / surcharge	Soft compressible clay	Load placed before construction to cause primary consolidation in advance. Surcharge greater than the design load also cuts secondary settlement.
Vertical sand drains / PVDs	Soft clay with preloading	Shorten the drainage path, so consolidation is mostly **radial** (Barron's theory). Sand drains: 200–600 mm diameter at 2–5 m spacing. **PVD (wick drain)**: about 100 × 4 mm; equivalent diameter $d_w = 2(a + b)/\pi$. Influence zone d_e = **1.05s (triangular)** or **1.128s (square)**. Disturbance is called the **smear effect**.
Stone columns (IS 15284 Part 1:2003)	Soft clays, silts, loose silty sand (c_u about 7–50 kPa)	Columns 0.6–1.0 m in diameter at 2–3D spacing. They reinforce the soil, act as drains, raise bearing capacity, cut settlement and lower **liquefaction** potential.
Grouting	Sands and gravels (permeation); all soils (compaction or jet grouting); rock fissures	Types: **permeation** (cement, bentonite, chemical such as sodium silicate + $CaCl_2$ in the Joosten two-shot process), **compaction grouting** (stiff grout displaces soil), **jet grouting** (soilcrete columns), **fracture** (claquage) grouting. Groutability ratio N = $D_{15(soil)}/D_{85(grout)}$ > 25.
Soil nailing	Cuts in stiff clay, dense sand, weathered rock	Passive steel bars, **top-down** construction, inclined about 10–20° below horizontal at about 1–2 m spacing, with a shotcrete facing
Reinforced earth (Henri Vidal, France, 1960s)	Granular, free-draining backfill	Tensile strips or geogrids plus facing panels. Built **bottom-up**. Used for RE walls at flyover approaches (MoRTH Section 3100).
Dewatering	Excavations below the water table	Sumps and open pumping. **Well points**: one stage lowers the water about **5–6 m**; use multistage for deeper lowering. Deep wells. **Electro-osmosis** for **silts and clays** (k about 10^{-5}–10^{-7} cm/s). Freezing as a temporary method.

Stabilisation	Best for	Key facts
Mechanical	Granular soils	Blending soils to a suitable gradation plus compaction; for low-cost roads

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Cement	**Sandy/granular soils**, low PI (about < 10–15)	About 5–10% cement. Soil-cement for bases. Organic matter and sulphates are harmful.
Lime	**Clayey, plastic soils** (PI > about 10), expansive soils	About 2–8% lime. Effects: **cation exchange and flocculation** (PI falls, workability rises immediately), then **pozzolanic** reaction (long-term strength).
Bitumen	Sandy soils, low plasticity	Water-proofing and binding (sand-bitumen); cut-back or emulsion
Chemical	Various	$CaCl_2$ (holds moisture, dust palliative), NaCl, sodium silicate, polymers, fly ash

Geosynthetic	Primary function
Geotextile (woven / non-woven)	**Separation, filtration**, drainage, reinforcement (woven), protection
Geogrid	**Reinforcement** (open apertures interlock with soil): RE walls, base courses
Geomembrane	**Barrier / containment** (impervious): landfill liners, canal linings, ponds
Geonet / geocomposite drain	**In-plane drainage**
Geocell	Confinement of fill on slopes and in road bases
Geosynthetic clay liner (GCL)	Barrier (bentonite between geotextiles)

- **Expansive (black cotton) soils** have a high montmorillonite content, high swelling and shrinkage, wide deep cracks in summer and very low strength when wet.
  - **Free swell index** (IS 2720 Part 40:1977) = $(V_{water} - V_{kerosene})/V_{kerosene} \times 100$. A value above 50% means very high expansiveness (IS 1498: < 20 low, 20–35 moderate, 35–50 high). **Swelling pressure** is IS 2720 Part 41:1977.
  - Remedies: **under-reamed piles**; going below the active zone (about 3.5 m); **CNS (cohesive non-swelling) layer**; lime stabilisation; sand cushion; moisture barriers and wide aprons; removal and replacement; belled piers; flexible construction.
  - **CNS layer** (IS 9451:1994 for canal linings in expansive soils): CNS material has clay 15–20%, silt 30–40%, sand 30–40%, gravel 0–10%, **LL 30–50**, PI 15–30 and swelling pressure ≤ **10 kN/m²**. For canals of 2 cumecs and more, the layer thickness is **0.75 m** (swelling pressure 50–150 kN/m²), **0.85 m** (150–300) and **1.0 m** (300–500); smaller canals need 0.3–0.75 m. It counteracts swelling by its weight and cohesion.
- **Liquefaction** is the loss of shear strength when pore pressure rises to equal the total stress ($\sigma' \to 0$) under cyclic or earthquake loading.
  - Most susceptible: **loose, saturated, uniformly graded fine sand** (D_{50} ≈ 0.075–0.2 mm, low N, shallow water table). Classic cases: Niigata and Alaska, 1964.
  - Assessed by the Seed–Idriss simplified procedure, CSR vs CRR (IS 1893 Part 1:2016).
  - Remedies: densification (vibroflotation, dynamic compaction), stone columns or gravel drains, grouting, lowering the water table, piles taken below the liquefiable layer.

CODE UPDATE

Seismic design and the liquefaction annex are in IS 1893 (Part 1):2016, which replaced the 2002 edition. Flexible pavement design using CBR follows IRC 37:2018. The pile codes IS 2911 (Part 1, Sections 1–4) were revised in 2010 and Part 4 (load test) in 2013.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Maximum area ratio for an undisturbed sample? → **10%**.
- Inside clearance of a sampler should be? → **1–3%**.
- Vibroflotation is best suited to? → **Loose cohesionless (sandy) soils**.
- Geosynthetic used mainly as a barrier/liner? → **Geomembrane**.
- Lime stabilisation is most effective for? → **Clayey (plastic) soils**.
- Which geophysical method fails when a soft layer lies under a hard layer? → **Seismic refraction**.

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7. Fluid Mechanics & Hydraulics

NOTE

Fluid mechanics gives about 6–9 questions in SSC JE / AE / PSU civil papers. The usual questions ask for a standard value (Cd of a venturimeter, Vmax/Vavg, Cc of an orifice), a formula (centre of pressure, capillary rise, hydraulic jump energy loss), a classification (which turbine for which head, which dimensionless number for which flow) or a scale ratio (Froude model law). Learn the tables in this chapter. Most numericals are one-step substitutions.

7.1 Fluid Properties ★★★

- **Fluid** = a substance that **deforms continuously** under a shear stress, however small. A fluid at rest has **no shear stress**.
- **Mass density** ρ = mass/volume (kg/m³). Water: **1000 kg/m³ at 4 °C**, which is its maximum density. Mercury: **13,600 kg/m³**. Air: **1.225 kg/m³** (15 °C, sea level).
- **Specific weight** (weight density) γ = ρg (N/m³). Water: **9.81 kN/m³**.
- **Specific volume** = 1/ρ (m³/kg). It is the reciprocal of density.
- **Specific gravity** (relative density) $S = \rho_{liquid}/\rho_{water\ at\ 4\ °C}$. It is **dimensionless**. Mercury **13.6**; sea water ≈ **1.025**.
- **Viscosity** = resistance to shear (relative motion between layers). It is caused by **cohesion** in liquids and by **molecular momentum exchange** in gases.
- When temperature rises, the viscosity of a **liquid decreases** and the viscosity of a **gas increases**.
- **Newton's law of viscosity**: τ = μ (du/dy). du/dy = velocity gradient = rate of shear strain (rate of angular deformation).
- **Dynamic viscosity μ**: SI unit N·s/m² (Pa·s); CGS unit **poise** = 1 dyne·s/cm² = **0.1 N·s/m²**. 1 centipoise = 10^{-3} Pa·s, which is about the viscosity of water at 20 °C.
- **Kinematic viscosity ν = μ/ρ**: SI unit m²/s; CGS unit **stoke** = 1 cm²/s = **10^{-4} m²/s**. Water ≈ 1 **centistoke = 10^{-6} m²/s** (20 °C). Air ≈ 1.5 × 10^{-5} m²/s.
- Dimensions: μ → **$ML^{-1}T^{-1}$**; ν → **L^2T^{-1}**. ν contains no mass term.
- **Ideal fluid**: incompressible with **zero viscosity**. It does not exist in nature. A **real fluid** has viscosity.

Fluid type	Rheology ($\tau = A(du/dy)^n + \tau_0$)	Examples
Newtonian	Straight line through origin; n = 1, $\tau_0 = 0$	Water, air, kerosene, petrol, thin oils
Dilatant (shear-thickening)	**n > 1**; apparent viscosity rises with shear rate	Butter, quicksand, rice starch / sugar in water, concentrated sand slurry
Pseudoplastic (shear-thinning)	**n < 1**	Blood, milk, paper pulp, paints, polymer solutions
Bingham plastic (ideal plastic)	n = 1 with a **yield stress τ_0**	Toothpaste, sewage sludge, drilling mud
Thixotropic	Apparent viscosity **falls with time** of shearing	Printer's ink, lipstick, enamel paints
Rheopectic	Apparent viscosity **rises with time**	Gypsum paste, bentonite suspension
Ideal fluid	Lies along the du/dy axis (τ = 0)	None in nature
Ideal solid (elastic)	Lies along the τ axis (no flow)	None in nature

- **Surface tension σ** = force per unit length (N/m), which is numerically equal to surface energy per unit area (J/m²). It is due to **cohesion** at the free surface. Dimension **MT^{-2}**. Water–air at 20 °C ≈ **0.073 N/m**; mercury–air ≈ **0.48 N/m**. σ **decreases** as temperature rises.
- **Capillarity**: water **rises** in a glass tube because **adhesion > cohesion** (wetting, θ ≈ 0°). Mercury is **depressed** because **cohesion > adhesion** (θ ≈ **130°–140°**, so cos θ is negative).
- Capillary rise is inversely proportional to tube diameter. Use tubes of **> 6 mm** diameter in piezometers to keep the capillary error small.
- **Compressibility** = 1/K. **Bulk modulus K** = −dp/(dV/V) = dp/(dρ/ρ). Water K ≈ **2.1–2.2 GPa (2.1 × 10^9 N/m²)**, so water is treated as incompressible. K has the units of pressure.
- For a gas, K = **p** in an isothermal process and K = **kp** (k = c_p/c_v) in an adiabatic process.
- **Vapour pressure** = the partial pressure of the vapour in equilibrium with its liquid. It **rises with temperature**. Water: ≈ **2.34 kPa at 20 °C** and **101.3 kPa at 100 °C** (boiling). Mercury has a very low vapour pressure, which is why it is used in barometers.
- **Cavitation**: when local pressure falls **below the vapour pressure**, vapour bubbles form. They collapse in high-pressure zones, which causes pitting, noise, vibration and loss of efficiency. It is found in turbine runners, draft tubes, pump impeller eyes, spillway surfaces and siphons.
- **Continuum** assumption is valid when the mean free path is much smaller than the body dimension (Knudsen number **Kn < 0.01**).

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KEY FORMULAE

- Pressure inside a liquid **droplet**: $\Delta p = 4\sigma/d$ (one surface)
- Pressure inside a **soap bubble**: $\Delta p = 8\sigma/d$ (two surfaces)
- Pressure inside a liquid **jet**: $\Delta p = 2\sigma/d$
- **Capillary rise** in a tube: $h = 4\sigma \cos\theta/(\rho g d)$. For water ($\theta = 0$) in mm: $h \approx 30/d$ (d in mm).
- Capillary rise between two parallel plates a gap t apart: $h = 2\sigma \cos\theta/(\rho g t)$
- Shear stress $\tau = \mu u/t$ for a thin film; torque on a journal bearing $T = \mu \pi^2 D^3 N L/(120\, t)$

Standard value	Water (≈20 °C)	Air (≈20 °C, 1 atm)
Density	**998–1000 kg/m³**	**1.2 kg/m³**
Dynamic viscosity	**1.0×10^{-3} Pa·s**	1.8×10^{-5} Pa·s
Kinematic viscosity	**1.0×10^{-6} m²/s**	1.5×10^{-5} m²/s (≈15 times water)
Bulk modulus	2.1×10^{9} Pa	1.0×10^{5} Pa (isothermal) / 1.4×10^{5} Pa (adiabatic)
Sonic velocity	**≈ 1440–1480 m/s**	**≈ 340 m/s**
Surface tension	0.073 N/m	—

MEMORY TRICK

Pressure excess goes **Jet 2, Drop 4, Bubble 8** (each × σ/d). A bubble has two skins, so it doubles the drop. A jet is a cylinder with one curvature, so it halves the drop.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- 1 poise equals? → **0.1 N·s/m²**.
- Unit of kinematic viscosity in CGS? → **Stoke (cm²/s)**.
- Toothpaste behaves as? → **Bingham plastic**.
- Viscosity of a gas when temperature increases? → **Increases**.
- Excess pressure in a soap bubble of diameter d? → **8σ/d**.
- Why is mercury depressed in a glass capillary? → **Cohesion > adhesion ($\theta > 90°$)**.

7.2 Fluid Statics, Pressure Measurement & Buoyancy ★★★

- **Pascal's law**: pressure at a point in a fluid at rest is **equal in all directions**. The hydraulic press, jack and lift work on this principle.
- **Hydrostatic law**: $dp/dz = -\rho g$, so $p = \rho g h$. Pressure depends only on depth, not on the shape of the vessel (**hydrostatic paradox**).
- **Absolute pressure = atmospheric + gauge. Vacuum (negative gauge) pressure = atmospheric − absolute**.
- **Standard atmosphere = 101.325 kPa = 10.33 m of water = 760 mm of Hg** = 1.01325 bar. 1 bar = 10^5 Pa. 1 kgf/cm² = 98.1 kPa ≈ 10 m of water.
- Pressure head $h = p/(\rho g)$. For a liquid of specific gravity S, $h_{water} = S \times h_{liquid}$.
- **Barometer** measures atmospheric (absolute) pressure. A water barometer would need a column about 10.3 m tall.
- Atmospheric pressure **decreases with altitude**. In the troposphere the temperature lapse rate is **6.5 °C/km**.

Device	Key points
Piezometer	Simplest device. Measures **moderate gauge pressure of liquids only**. It **cannot measure gas pressure or vacuum** (negative pressure).
Simple **U-tube manometer**	Measures gauge and **vacuum** pressure. Usually uses a heavy liquid (Hg).
Single-column (micro) manometer	One limb has a large reservoir (area ratio ≈ 100), so only one reading is needed. The **inclined** type gives higher sensitivity.
Differential U-tube	Pressure difference between two points: $p_A - p_B = g \times (\rho_m - \rho)$ (same level, same liquid).
Inverted U-tube	Uses a **lighter** liquid (air or oil) at the top. For **small** pressure differences between liquids.
Micromanometer	Two manometric liquids. For **very small** pressure differences.
Bourdon gauge	Mechanical gauge with an **elliptical cross-section tube** bent in a C shape. Reads **gauge pressure**; used for high pressures.
Diaphragm / bellows gauge	Low pressures; elastic element.
Pressure transducer	Electrical (strain gauge, piezoelectric). Used for fluctuating pressures.

KEY FORMULAE – HYDROSTATIC FORCES

- Total pressure on any plane surface: $\mathbf{F = \rho g A \bar{h}}$ ($\bar{h}$ = depth of the centroid)
- Centre of pressure, vertical surface: $\mathbf{h^* = \bar{h} + I_G/(A \bar{h})}$
- Centre of pressure, inclined surface (θ with free surface): $\mathbf{h^* = \bar{h} + I_G \sin^2\theta/(A \bar{h})}$
- Horizontal surface: $F = \rho g A h$ and the centre of pressure coincides with the centroid.
- Curved surface: F_H = force on the vertical projection; **F_V = weight of liquid above the surface** (up to the free surface); $F = \sqrt{(F_H^2 + F_V^2)}$, $\tan\theta = F_V/F_H$.
- Force on a dam (unit width, depth H): $F = \rho g H^2/2$, acting at **H/3 above the base**.

- The centre of pressure always lies **below the centroid** (except on a horizontal surface). As the surface is lowered deeper, the centre of pressure **approaches the centroid**.

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Vertical surface (top edge or apex at free surface)	Depth of centre of pressure h*
Rectangle of depth d	**2d/3**
Triangle, **vertex** at surface, base down (height h)	**3h/4**
Triangle, **base** at surface, vertex down (height h)	**h/2**
Circle of diameter d, touching the surface	**5d/8**

- **Archimedes' principle**: buoyant force = **weight of fluid displaced**. It acts vertically upward through the **centre of buoyancy (B)**, which is the centroid of the displaced volume.
- Floating body: weight = buoyancy. Fraction submerged = $\rho_{body}/\rho_{liquid}$.
- **Metacentre (M)** = the point where the line of action of buoyancy cuts the body's axis after a small angular tilt.
- **Metacentric height GM = BM − BG**, with **BM = I/V**. I = least moment of inertia of the **water-line plane** about the longitudinal (tilt) axis; V = displaced volume.
- Experimental: GM = w x/(W tan θ), where a weight w is moved a distance x across the deck and causes a heel θ.

Condition	Floating body	Fully submerged body (balloon, submarine)
Stable	**M above G** (GM > 0)	**B above G**
Unstable	M below G (GM < 0)	B below G
Neutral	M coincides with G	B coincides with G

- **Time period of rolling**: $T = 2\pi\sqrt{(k^2/(g \cdot GM))}$, where k = radius of gyration. A **large GM gives a short period**, which means a stiff and uncomfortable roll. **Passenger ships** are built with a **small GM** for comfort. **Warships** and racing yachts are given a larger GM for stability.
- **Liquid in a tank with horizontal acceleration a**: the free surface slopes at tan θ = a/g. With vertical acceleration a, p = ρh(g ± a).
- **Forced vortex in a rotating cylinder**: the free surface is a **paraboloid** with $z = \omega^2 r^2/2g$. The volume of the paraboloid is **half** the volume of the circumscribing cylinder, so the rise at the wall equals the fall at the centre.

MEMORY TRICK

"**M over G, ship is free**" (stable). For anything fully submerged, think "**B over G**", because a fully submerged body has no metacentre to use.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Standard atmospheric pressure in metres of water? → **10.3 m**.
- Which device cannot measure negative pressure? → **Piezometer**.
- Centre of pressure of a vertical rectangle with its top edge at the free surface? → **2/3 of the depth**.
- Metacentric height formula? → **GM = I/V − BG**.
- Stability condition for a submarine? → **B above G**.
- Pressure on a dam acts at what height? → **H/3 from the base**.

7.3 Fluid Kinematics ★★☆

Flow type	Definition	Example
Steady	$\partial(V, p, \rho)/\partial t = 0$ at a point	Constant discharge through a pipe
Unsteady	Properties change with time	Flood wave, emptying a tank
Uniform	$\partial V/\partial s = 0$ (no change along the flow at an instant)	Long straight pipe of constant diameter
Non-uniform	Velocity changes along the flow	Tapering pipe, river
Laminar	Particles move in layers; viscous forces dominate	Blood in capillaries, oil, groundwater
Turbulent	Random mixing; inertia dominates	Rivers, most pipe flows of water
Rotational	Particles rotate about their own axes (ω ≠ 0)	Forced vortex, flow near walls
Irrotational	ω = 0	Free vortex, ideal flow outside boundary layers
Compressible	ρ varies (Mach > 0.3)	Gas at high speed
1-D / 2-D / 3-D	Number of space coordinates needed	Pipe (1-D, in the average sense)

- Steady uniform: constant discharge in a straight pipe of constant diameter. **Steady non-uniform**: constant discharge in a **tapering** pipe. Unsteady uniform: varying discharge in a constant-diameter pipe. Unsteady non-uniform: varying discharge in a tapering pipe.
- **Streamline**: a line tangent to the velocity vector at every point. **No flow crosses a streamline**, and two streamlines can never intersect.
- **Pathline**: the actual path traced by one particle over time. **Streakline**: the locus of all particles that passed through a fixed point (for example, a dye filament).
- In **steady flow, streamlines, pathlines and streaklines coincide**.
- **Stream tube**: a bundle of streamlines. Fluid cannot cross its wall.
- **Continuity equation** = conservation of **mass**: $\rho_1 A_1 V_1 = \rho_2 A_2 V_2$. For an incompressible fluid, $Q = A_1 V_1 = A_2 V_2$.

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- General 3-D incompressible form: $\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0$. This holds for **steady or unsteady** incompressible flow.
- **Acceleration** = **local** ($\partial u/\partial t$, due to unsteadiness) + **convective** ($u\partial u/\partial x + v\partial u/\partial y + w\partial u/\partial z$, due to non-uniformity). Steady flow has zero local acceleration. Uniform flow has zero convective acceleration.
- Tangential and normal acceleration: $a_s = V\,\partial V/\partial s + \partial V/\partial t$; $a_n = V^2/r + \partial V_n/\partial t$.

Item	Velocity potential φ	Stream function ψ
Exists when	Flow is **irrotational** (2-D or 3-D)	Flow is **2-D** and continuity is satisfied (rotational or irrotational)
Velocity (Bansal sign convention)	$u = -\partial\varphi/\partial x$, $v = -\partial\varphi/\partial y$	$u = -\partial\psi/\partial y$, $v = \partial\psi/\partial x$
Laplace equation $\nabla^2 = 0$	Satisfied if the flow is **incompressible** (continuity)	Satisfied if the flow is **irrotational**
Constant-value lines	Equipotential lines	Streamlines
Key property	Its existence proves irrotationality	**$\psi_2 - \psi_1$ = discharge per unit width** between the two streamlines

- Many books use $u = \partial\varphi/\partial x$ and $u = \partial\psi/\partial y$, $v = -\partial\psi/\partial x$. The signs are only a convention, and the results do not change.
- Streamlines and equipotential lines are **orthogonal**: the product of their slopes is **−1**.
- **Rotation** $\omega_z = \tfrac{1}{2}(\partial v/\partial x - \partial u/\partial y)$. **Vorticity** $\Omega = 2\boldsymbol{\omega}$. Flow is irrotational when $\partial v/\partial x = \partial u/\partial y$.
- **Circulation Γ** = $\oint V\cdot ds$ (line integral around a closed curve) = **vorticity × area**. Γ = 0 for irrotational flow, except around a singularity.
- **Flow net**: a grid of streamlines and equipotential lines forming **curvilinear squares**. It is valid only for **steady, irrotational, incompressible** flow. It fails near solid boundaries and in separation zones. It is used for **seepage** under dams, flow under sheet piles and uplift pressure.
- Seepage discharge from a flow net: $q = k\,H\,N_f/N_d$ (N_f = number of flow channels, N_d = number of potential drops).

Item	Free vortex	Forced vortex
External torque	None	Applied (rotated by an external agent)
Velocity law	**V × r = constant**	**V = ω r**
Nature	**Irrotational**; Bernoulli applies across streamlines	**Rotational**; rotates like a solid body
Surface profile	Hyperbolic (deepest at the centre)	Paraboloid, $z = \omega^2 r^2/2g$
Examples	Whirlpool, water draining from a wash-basin, flow in a centrifugal pump **casing**, flow round a river bend	Liquid in a rotating vessel, flow **inside the impeller** of a centrifugal pump

PREVIOUSLY ASKED / LIKELY QUESTIONS

- When do streamlines, pathlines and streaklines coincide? → **In steady flow**.
- Flow through a tapering pipe at constant discharge? → **Steady, non-uniform**.
- Velocity potential exists only for? → **Irrotational flow**.
- Difference of stream function between two streamlines gives? → **Discharge per unit width**.
- Vorticity equals how many times the rotation? → **Twice**.
- Flow inside a centrifugal pump impeller is an example of? → **Forced vortex**.

7.4 Fluid Dynamics – Bernoulli & Momentum ★★½

- **Euler's equation** (along a streamline): $dp/\rho + g\,dz + V\,dV = 0$. Assumptions: **ideal (non-viscous)**, **steady** flow, flow **along a streamline**, and only gravity and pressure forces act.
- **Bernoulli's equation** = Euler's equation integrated for an **incompressible** fluid: $\mathbf{p/\rho g + V^2/2g + z = constant}$. It is the **energy** equation (energy per unit weight = head, in m).
- The four Bernoulli assumptions: **ideal, steady, incompressible, along a streamline**. If the flow is also irrotational, the constant is the same everywhere.
- For a real fluid: $p_1/\rho g + V_1^2/2g + z_1 = p_2/\rho g + V_2^2/2g + z_2 + h_L$.
- **Navier–Stokes** equations include viscous forces. **Reynolds equations** are for turbulent flow.
- **HGL (hydraulic gradient line)** = locus of $p/\rho g + z$. **TEL (total energy line)** = HGL + $V^2/2g$, so the TEL is always above the HGL by the **velocity head**.
- Without a pump, the TEL always **falls** in the direction of flow. The HGL can **rise** where the velocity decreases (at an expansion).
- For constant-diameter pipe flow, the HGL and TEL are parallel. Where the HGL is below the pipe centreline, the pressure is **negative**.
- In open channels, the HGL coincides with the **free surface**.

Flow meter	C_d	Points to remember
Venturimeter	**0.95–0.99** (≈0.98)	Convergent cone angle ≈ **20–21°**; divergent cone **5–7°** (longer, to avoid separation); throat d = **1/3 to 3/4 D** (usually D/2). The manometer reading does **not** depend on inclination.
Orifice meter	**0.60–0.65** (≈0.62)	Orifice d ≈ D/2. Cheap and compact but gives a **large head loss**. Vena contracta lies downstream.

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Flow nozzle	**0.93–0.98**	Between the venturi and the orifice meter in cost and loss.
Pitot tube	$C_v \approx 0.98–1$	Measures **velocity at a point** from stagnation pressure: $V = C_v\sqrt{(2gh)}$. The pitot-static tube measures the dynamic head directly.
Rotameter	—	**Variable-area** meter; a float in a tapered tube.
Current meter	—	Velocity in **rivers and open channels** (cup type / propeller type).
Hot-wire anemometer	—	Turbulent fluctuations of gas velocity.

KEY FORMULAE

- Venturi, orifice or nozzle meter: $\mathbf{Q = C_d\, a_1a_2\sqrt{(2gh)}/\sqrt{(a_1^2 - a_2^2)}}$
- Differential head with a heavier manometric liquid: $h = x(S_m/S - 1)$. For Hg and water: **h = 12.6 x**.
- With a lighter manometric liquid (inverted U-tube): $h = x(1 - S_l/S)$
- Pitot tube: $V = C_v\sqrt{(2g\Delta h)}$
- **Momentum equation** (impulse–momentum): $\mathbf{\Sigma F = \rho Q(V_2 - V_1)}$ (a vector equation). Its correction factor is β.
- Force on a pipe bend: $F_x = \rho Q(V_{1x} - V_{2x}) + p_1A_1 - p_2A_2\cos\theta$; $F_y = \rho Q(0 - V_2\sin\theta) - p_2A_2\sin\theta$ (magnitude). The bend is anchored by **thrust blocks**.
- **Moment of momentum**: $T = \rho Q(V_2r_2 - V_1r_1)$. This is the basis of turbine and pump theory and of the lawn sprinkler.

Impact of jet (area a, velocity V, plate speed u)	Force	Max efficiency
Stationary flat plate, normal to jet	ρaV^2	—
Stationary flat plate inclined at θ to the jet (normal force)	$\rho aV^2\sin\theta$	—
Stationary curved vane, jet deflected through 180° (symmetrical, striking at the centre)	$2\rho aV^2$	—
Single moving flat plate	$\rho a(V - u)^2$	**8/27 (29.6%)** at u = V/3
Series of flat plates (radial plates on a wheel)	$\rho aV(V - u)$	**50%** at **u = V/2**
Series of curved (semicircular) vanes, as in Pelton	$2\rho aV(V - u)$	**100%** (theoretical) at **u = V/2**
Single moving curved vane (180°)	$2\rho a(V - u)^2$	—

MEMORY TRICK

"**Venturi Very good (0.98), Orifice Ordinary (0.62), Nozzle in between (0.95).**" For a single plate the best speed is **V/3**. For any **series** of plates or vanes it is **V/2**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Bernoulli's theorem is based on the conservation of? → **Energy**.
- Vertical gap between TEL and HGL? → **Velocity head $V^2/2g$**.
- Why is the divergent cone of a venturimeter longer? → **To avoid flow separation (angle 5–7°)**.
- Pitot tube measures? → **Velocity at a point (stagnation pressure)**.
- Force of a jet on a stationary flat plate held normal to it? → **ρaV^2**.
- Max efficiency of a jet striking a series of flat plates? → **50%**.

7.5 Orifices, Mouthpieces, Notches & Weirs ★★★

- **Orifice** = an opening in the wall or base of a tank. It is **small** if the head is more than 5 × its depth, and **large** otherwise. A **mouthpiece** is a short tube of length **2–3 d** fitted to an orifice.
- **Vena contracta** = the section of minimum area and parallel streamlines, at about **d/2** from the orifice.
- **Coefficient of contraction C_c** = a_c/a = **0.61–0.69 (≈0.64)**.
- **Coefficient of velocity C_v** = actual $V/\sqrt{(2gH)}$ = **0.95–0.99 (≈0.97–0.98)**.
- **Coefficient of discharge $C_d = C_c \times C_v$** = **0.61–0.65 (≈0.62)**.
- Coefficient of resistance C_r = loss of head/actual velocity head = $1/C_v^2 - 1$.
- C_v by the **trajectory method**: $C_v = x/\sqrt{(4yH)}$, with x and y the horizontal and vertical coordinates of the jet.
- Large rectangular orifice: $Q = (2/3)\, C_d\, b\sqrt{(2g)}(H_2^{3/2} - H_1^{3/2})$. Fully submerged orifice: $Q = C_d\, a\sqrt{(2gH)}$, where H = difference of the water levels on the two sides.

KEY FORMULAE – TIME OF EMPTYING (ORIFICE AREA A AT THE BOTTOM)

- Prismatic tank of area A, from H_1 to H_2: $\mathbf{T = 2A(\sqrt{H_1} - \sqrt{H_2})/(C_d\, a\sqrt{(2g)})}$
- Complete emptying: $T = 2A\sqrt{H}/(C_d\, a\sqrt{(2g)})$. **Time ∝ √H**; this is twice the time needed to discharge the same volume under a constant head H.
- Hemispherical tank of radius R: $T = \pi[(4/3)R(H_1^{3/2} - H_2^{3/2}) - (2/5)(H_1^{5/2} - H_2^{5/2})]/(C_d\, a\sqrt{(2g)})$. Full emptying from H = R: $T = 14\pi R^{5/2}/(15\, C_d\, a\sqrt{(2g)})$.

Mouthpiece	C_c	C_v	C_d
External cylindrical (length 2–3d)	1.0 (at outlet)	0.855	**0.855**
Convergent–divergent	1.0	≈1	**≈1.0** (on throat area); smallest loss
Borda's (re-entrant) running free	0.5	1.0	**0.5**

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Borda's running full	1.0	0.707	**0.707**

- An external mouthpiece gives about **one-third more discharge** than a sharp orifice of the same diameter (0.855 vs 0.62–0.64). The pressure at its vena contracta is **below atmospheric**: absolute pressure head = H_{atm} − 0.89 H.
- **Notch** = an opening in the side of a measuring tank or small channel. **Weir** = a concrete or masonry structure across a river or channel. The sheet of water over it is the **nappe** (vein).
- The nappe must be **ventilated**. Without air the pressure below the nappe falls, the nappe becomes **depressed or clinging**, and the **discharge increases**, so the weir formula no longer gives the correct value.

KEY FORMULAE – NOTCHES & WEIRS

- **Rectangular**: Q = **(2/3) C_d b √(2g) $H^{3/2}$** (with C_d = 0.62: Q ≈ 1.83 b $H^{3/2}$)
- **Triangular (V)**: Q = **(8/15) C_d tan(θ/2) √(2g) $H^{5/2}$**. For a 90° notch with C_d = 0.6: **Q = 1.417 $H^{5/2}$** m^3/s.
- **Trapezoidal** = rectangular part + triangular part (sum of the two formulae)
- **Cipolletti** (trapezoidal with sides **1 H : 4 V**, θ/2 = 14°2′): **Q = 1.86 L $H^{3/2}$**. The triangular portions **exactly compensate the end contractions**.
- **Francis' formula** (end contractions): **Q = 1.84 (L − 0.1 n H) $H^{3/2}$**; n = number of end contractions (2 for a weir with both ends contracted). Each contraction reduces the effective length by **0.1H**.
- Velocity of approach ($h_a = V_a^2/2g$): Q = (2/3)C_d L √(2g)[(H + h_a)$^{3/2}$ − $h_a^{3/2}$]
- Bazin's formula: Q = m L √(2g) $H^{3/2}$, with m = 0.405 + 0.003/H
- **Broad-crested weir**: Q_{max} = **1.705 C_d L $H^{3/2}$**, reached when the depth over the crest = **2H/3** (critical depth)
- Submerged (drowned) weir: Q = $Q_{free\ part}$ + $Q_{drowned\ part}$ = (2/3)C_dL√(2g)(H_1 − H_2)$^{3/2}$ + C_dL H_2√(2g(H_1 − H_2))
- **Error in discharge due to an error in head**: rectangular **dQ/Q = (3/2) dH/H**; triangular **dQ/Q = (5/2) dH/H**

Weir / notch	Use / feature
Rectangular notch	Medium and large flows; Q ∝ $H^{3/2}$
V-notch	**Most accurate for small discharges**. C_d is fairly constant, only one reading (H) is needed, and no ventilation is required. Q ∝ $H^{5/2}$.
Cipolletti	No end-contraction correction needed
Sharp-crested (narrow)	Crest width < 0.5 H
Broad-crested	Crest width > 0.5 H; flow becomes critical over the crest
Ogee weir / spillway	Crest shaped to the lower nappe of a sharp-crested weir, so the pressure on the crest is about atmospheric. Q = (2/3)C_dL√(2g)$H^{3/2}$.
Stepped / Sutro (proportional)	Sutro weir: Q ∝ H (linear). Used as a velocity-control device in grit chambers.

MEMORY TRICK

The **power of H** gives the error factor: Q ∝ $H^{3/2}$ gives 1.5 × % error and Q ∝ $H^{5/2}$ gives 2.5 × % error. **Cipolletti = "1 : 4, no correction"**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Relation between C_d, C_c and C_v? → **$C_d = C_c \times C_v$**.
- C_d of an external cylindrical mouthpiece? → **0.855**.
- C_d of Borda's mouthpiece running free? → **0.5**.
- Side slope of a Cipolletti weir? → **1 H : 4 V**.
- A 1% error in measuring head over a V-notch causes what error in Q? → **2.5%**.
- Discharge over a rectangular notch varies as? → **$H^{3/2}$**.

7.6 Laminar & Turbulent Flow in Pipes ★★★

- **Reynolds number** Re = ρVD/μ = VD/ν = **inertia force/viscous force**. Reynolds' dye experiment dates from 1883.
- Pipe flow: **Re < 2000 laminar**; **2000–4000 transitional**; **> 4000 turbulent**. Between parallel plates the laminar limit is ≈ 1000. In open channels (Re based on R) the flow is laminar below **500** and turbulent above **2000**.
- The **lower critical Re** (≈ 2000) is the significant one. The upper critical value is unstable and depends on the disturbances present.

KEY FORMULAE – LAMINAR FLOW

- **Hagen–Poiseuille**: Δp = **32 μ V L/D^2**; h_f = 32μVL/(ρgD^2) = **128 μ Q L/(π ρ g D^4)**. h_f ∝ V (not V^2).
- Darcy friction factor: **f = 64/Re**. With the Indian-text coefficient f′ (h_f = 4f′LV^2/2gD): **f′ = 16/Re**.
- Velocity profile in a pipe (**parabolic**): u = u_{max}(1 − r^2/R^2); **u_{max} = 2 V_{avg}**. The local velocity equals V_{avg} at **r = 0.707 R**.
- Shear stress varies **linearly**: zero at the centre and maximum at the wall. τ = (−dp/dx)(r/2); τ_0 = (−dp/dx)(R/2) = ρgh_fD/(4L).
- Between two fixed parallel plates (gap t): **u_{max} = 1.5 V_{avg}**; Δp = **12 μ V L/t^2**.
- Laminar entry length ≈ 0.07 Re D.

Correction factor	Pipe (laminar)	Plates (laminar)	Turbulent
Kinetic energy α = (1/AV^3)∫u^3dA	**2.0**	**1.543** (54/35)	1.03–1.10 (≈1)
Momentum β = (1/AV^2)∫u^2dA	**4/3 = 1.33**	**1.2** (6/5)	1.01–1.04 (≈1)
u_{max}/V_{avg}	**2.0**	**1.5**	≈ 1.2 (1/7 power law)

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- For a non-uniform velocity profile $\alpha > \beta > 1$ always. Both equal 1 only for a uniform profile.
- **Turbulent flow**: the velocity profile is **flatter** (logarithmic, or the 1/7 power law $u/u_{max} = (y/R)^{1/7}$). Shear = viscous + **Reynolds (turbulent) stress**. Prandtl introduced the **mixing length**; Boussinesq the eddy viscosity.
- **Shear (friction) velocity** $u_* = \sqrt{(\tau_0/\rho)}$. **Laminar sub-layer** thickness $\delta' = \mathbf{11.6\ \nu/u_*}$.
- Hydraulically **smooth** when $k/\delta' < 0.25$; **rough** when $k/\delta' > 6$ (Nikuradse); transitional in between. The same pipe can be smooth at low Re and rough at high Re.
- Turbulent smooth pipe (**Blasius**, $4000 < Re < 10^5$): $f = \mathbf{0.316/Re^{1/4}}$ ($f' = 0.079/Re^{1/4}$). Fully rough flow: f depends only on k/D (Re has no effect).
- **Moody chart**: f against Re for different relative roughness k/D, based on the **Colebrook–White** equation. In fully rough flow, $h_f \propto V^2$.

KEY FORMULAE – PIPE FRICTION

- **Darcy–Weisbach**: $\mathbf{h_f = f\,L\,V^2/(2\,g\,D)} = f\,L\,Q^2/(12.1\,D^5)$ (f = Darcy friction factor ≈ 0.02 for typical pipes)
- Indian textbooks (Bansal, Modi & Seth): $h_f = \mathbf{4\,f\,L\,V^2/(2\,g\,D)}$, where f = coefficient of friction = Darcy f/4. Check which "f" the question uses.
- $h_f \propto 1/D^5$ at constant Q. Halving D raises h_f about **32 times**.
- **Hazen–Williams** (SI): $V = \mathbf{0.849\,C\,R^{0.63}\,S^{0.54}}$. CPHEEO C values: new CI 130, DI (cement-lined) 140, PVC/HDPE 150, RCC 140 (design values are lower). A higher C means a smoother pipe. The formula is used for **water supply** design.
- **Manning**: $V = (1/n)\,R^{2/3}\,S^{1/2}$. Used for **sewers** and open channels.
- **Chezy**: $V = C\sqrt{(R\,S)}$

Minor loss	Head loss
Sudden enlargement (Borda–Carnot)	$\mathbf{(V_1 - V_2)^2/2g}$
Sudden contraction	$(1/C_c - 1)^2\,V_2^2/2g$; usually taken as $\mathbf{0.5\,V_2^2/2g}$ ($\approx 0.375\,V_2^2/2g$ with $C_c = 0.62$)
Entrance (sharp-edged)	$\mathbf{0.5\,V^2/2g}$ (bell-mouthed ≈ 0.04)
Exit into a tank	$\mathbf{1.0\,V^2/2g}$ (all KE lost)
Obstruction in a pipe	$[A/(C_c(A - a)) - 1]^2\,V^2/2g$
Bend / fittings	$k\,V^2/2g$
Gradual expansion	$k\,(V_1 - V_2)^2/2g$; minimum loss at a cone angle of ≈ 6–8°

- Minor losses can be neglected when the pipe is longer than **1000 D** (a "long pipe").
- Equivalent length of a fitting: $L_e = kD/f$.
- **Pipes in series**: same Q; $H = \Sigma h_f$ + minor losses. **Pipes in parallel**: **same h_f** in each branch; $Q = \Sigma Q_i$.
- **Equivalent pipe (Dupuit's equation)**: $L/D^5 = L_1/D_1^5 + L_2/D_2^5 + \ldots$ (same f, $L = \Sigma L_i$).
- **Siphon**: a long pipe that rises above the hydraulic gradient. The summit is at **negative pressure**. Theoretically the summit must be less than 10.3 m above the supply level; in practice it is kept to **≈ 7.5–8 m** so that dissolved air does not come out and break the flow.
- **Pipe network**: solved by the **Hardy Cross** method. Correction $\Delta Q = -\Sigma r\,Q^n/(n\,\Sigma\,r\,Q^{n-1})$, with n = 2 for Darcy and 1.85 for Hazen–Williams.

KEY FORMULAE – POWER & WATER HAMMER

- Power transmitted through a pipe: $P = \rho g Q(H - h_f)$; efficiency $\eta = (H - h_f)/H$
- **Maximum power when $h_f = H/3$**, giving $\mathbf{\eta_{max} = 66.7\%}$
- Nozzle at the end of a pipe: max power when the friction loss is H/3; nozzle diameter $d = (D^5/(8f'L))^{1/4}$ (with $h_f = 4f'LV^2/2gD$)
- **Water hammer**, celerity $c = \sqrt{(K/\rho)} \approx$ **1440 m/s** in a rigid pipe. For an elastic pipe: $c = \sqrt{[(K/\rho)/(1 + KD/(Et))]}$.
- **Critical time $t_c = 2L/c$**. Valve closure is **rapid (sudden)** if $t < 2L/c$ and **gradual** if $t > 2L/c$.
- Sudden closure: pressure rise $\mathbf{p = \rho\,c\,V}$ (Joukowsky). Gradual closure: $p = \rho LV/t$.
- **Surge tank** (and air vessels or relief valves) protect penstocks against water hammer.

- **Boundary layer** (Prandtl, 1904) = the thin layer near a wall where viscous effects matter. **Thickness δ** is measured to the point where $u = \mathbf{0.99\,U}$.
- **Displacement thickness** $\delta^* = \int(1 - u/U)dy$. **Momentum thickness** $\theta = \int(u/U)(1 - u/U)dy$. **Energy thickness** $\delta_e = \int(u/U)(1 - u^2/U^2)dy$. The order is $\mathbf{\delta > \delta^* > \theta}$.
- **Shape factor $\mathbf{H = \delta^*/\theta = 2.59}$** for laminar flow (Blasius) and ≈ 1.3–1.4 for turbulent flow.
- Laminar flat plate (Blasius): $\mathbf{\delta = 5x/\sqrt{Re_x}}$ (4.91), $\delta^* = 1.72x/\sqrt{Re_x}$, $\theta = 0.664x/\sqrt{Re_x}$, $C_D = 1.328/\sqrt{Re_L}$. $\delta \propto x^{1/2}$.
- Turbulent flat plate: $\delta = 0.37x/Re_x^{1/5}$, so $\delta \propto x^{4/5}$. Transition on a flat plate occurs at $\mathbf{Re_x \approx 5 \times 10^5}$.
- **Separation** occurs under an **adverse pressure gradient ($\mathbf{dp/dx > 0}$)**. At the separation point $\mathbf{(\partial u/\partial y)_{y=0} = 0}$, and beyond it the gradient is negative (reversed flow). Control methods: suction, blowing, streamlining, rotating cylinders, slotted wings.
- **Drag** = skin friction + pressure (form) drag. A streamlined body has mainly friction drag; a bluff body mainly pressure drag.
- **Stokes' law** ($Re < 1$): $F_D = 3\pi\mu DV$, $C_D = 24/Re$. Settling velocity $V_s = g\,D^2(\rho_s - \rho)/(18\,\mu)$. Used for sedimentation tanks.
- **Magnus effect**: lift on a rotating cylinder or ball in a stream. Kutta–Joukowski: $L = \rho U\Gamma$ per unit length.

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MEMORY TRICK

"**2, 4/3, 64**" for a laminar pipe: α = 2, β = 4/3, f = 64/Re, and also $u_{max} = 2V_{avg}$. For plates, "**1.5 and 12**": $u_{max} = 1.5V$ and $\Delta p = 12\mu VL/t^2$. Losses at a pipe "**Enter half, Exit whole**" (0.5 and 1.0).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Ratio of maximum to average velocity in laminar pipe flow? → **2**.
- Friction factor for laminar flow? → **64/Re**.
- Condition for maximum power transmission through a pipe? → **h_f = H/3 (η = 66.7%)**.
- Loss of head at the exit of a pipe into a reservoir? → **$V^2/2g$**.
- Pressure rise due to sudden valve closure? → **ρcV**.
- Flow separation occurs when the pressure gradient is? → **Adverse (dp/dx > 0)**.

7.7 Dimensional Analysis & Similitude

★★☆

Quantity	Dimension	Quantity	Dimension
Velocity	LT^{-1}	Force	**MLT^{-2}**
Acceleration	LT^{-2}	Pressure, stress, K, E	**$ML^{-1}T^{-2}$**
Discharge	L^3T^{-1}	Work, energy, torque	**ML^2T^{-2}**
Kinematic viscosity	**L^2T^{-1}**	Power	**ML^2T^{-3}**
Dynamic viscosity	**$ML^{-1}T^{-1}$**	Momentum	MLT^{-1}
Density	ML^{-3}	**Surface tension**	**MT^{-2}**
Specific weight	**$ML^{-2}T^{-2}$**	Angular velocity, strain rate	T^{-1}
Chezy's C	**$L^{1/2}T^{-1}$**	Manning's n	**$L^{-1/3}T$**
Circulation, stream function (2-D)	L^2T^{-1}	Specific gravity, strain, f, angle	Dimensionless

- **Dimensional homogeneity** (Fourier): every term of a valid equation has the same dimensions.
- **Rayleigh's method**: suitable when there are few variables (up to about 3–4). It gives an exponent-based expression.
- **Buckingham π theorem**: n variables with m fundamental dimensions give **(n − m) π-terms**.
- Rules for **repeating variables**: they must not include the dependent variable; together they must contain all the fundamental dimensions; they must not form a dimensionless group among themselves; no two may have the same dimensions. The usual choice is one each for **geometry (D or L), flow (V) and fluid (ρ)**.
- **Similitude**: **geometric** (length ratios equal), **kinematic** (velocity and acceleration ratios equal), **dynamic** (force ratios equal). Complete similarity needs all three.

Number	Definition	Force ratio	Governs (model law)
Reynolds Re	ρVL/μ	Inertia/viscous	**Pipe flow**, fully submerged bodies (submarines, aircraft at low speed), flow meters
Froude Fr	$V/\sqrt{(gL)}$	√(Inertia/gravity)	**Free-surface flows**: open channels, spillways, weirs, hydraulic jumps, ship wave resistance, river models
Weber We	$V/\sqrt{(\sigma/\rho L)}$	√(Inertia/surface tension)	Capillary flows, droplets, very low heads over weirs, thin films
Euler Eu	$V/\sqrt{(p/\rho)}$	√(Inertia/pressure)	Pressure-dominated flows, **cavitation** studies
Mach M	V/c	√(Inertia/elastic)	**Compressible flow**, high-speed aircraft and projectiles, water hammer
Cauchy Ca	$\rho V^2/K$	Inertia/elastic	Compressible flow; **Ca = M^2**

KEY FORMULAE – MODEL SCALE RATIOS (L_R = PROTOTYPE/MODEL LENGTH)

- **Froude law** (same g, same fluid): velocity $V_r = \mathbf{L_r^{1/2}}$; time $T_r = \mathbf{L_r^{1/2}}$; acceleration $a_r = 1$; discharge $Q_r = \mathbf{L_r^{5/2}}$; force $F_r = \mathbf{L_r^3}$; pressure intensity $p_r = L_r$; work/energy = L_r^4; power $P_r = \mathbf{L_r^{7/2}}$; momentum = $L_r^{7/2}$
- **Reynolds law** (same fluid): $V_r = 1/L_r$; $T_r = L_r^2$; $Q_r = L_r$; $F_r = 1$
- Example: a 1:25 Froude model of a spillway gives $Q_r = 25^{2.5} =$ **3125** and $V_r =$ **5**
- **Distorted model** (horizontal scale L_r, vertical scale y_r): $V_r = \sqrt{y_r}$; $Q_r = L_r\, y_r^{3/2}$; Manning's $n_r = y_r^{2/3}/L_r^{1/2}$; distortion = L_r/y_r

- **Distorted models** are used for **rivers, harbours and estuaries**, where a true-scale model would make depths too small (surface-tension effects, laminar flow, unreadable depths). Drawbacks: the wave pattern and velocity distribution are not reproduced faithfully.
- An undistorted Froude model needs a roughness scale $n_r = L_r^{1/6}$.
- Satisfying Froude and Reynolds laws together needs $v_r = L_r^{3/2}$, which is usually impossible. The dominant force decides which law is used.
- **Scale effect** = the discrepancy between model and prototype results caused by forces that cannot be scaled.

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- Model law for spillway and open channel models? → **Froude's law**.
- Discharge scale ratio under Froude's law? → $L_r^{5/2}$.
- Dimensions of dynamic viscosity? → $ML^{-1}T^{-1}$.
- Number of π-terms for 7 variables in M, L, T? → **4**.
- Mach number governs which flows? → **Compressible flows**.
- Distorted models are used for? → **Rivers and harbours**.

7.8 Open Channel Flow ★★★

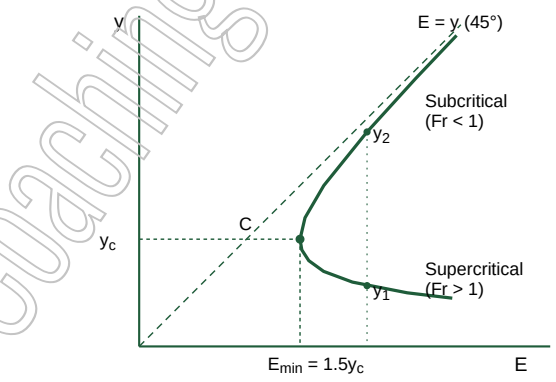
- An open channel has a **free surface at atmospheric pressure**. Flow is driven by **gravity** (bed slope). The HGL coincides with the water surface.
- Types of flow: **uniform** (depth constant along the channel; bed slope = water-surface slope = energy slope, $S_0 = S_w = S_f$) and **non-uniform/varied**. Varied flow is either **gradually varied (GVF)**, as in a backwater, or **rapidly varied (RVF)**, as in a hydraulic jump or flow over a weir. Spatially varied flow occurs in side-channel spillways and gutters.
- Hydraulic radius R = A/P. **Hydraulic depth D = A/T** (T = top width).
- The velocity distribution is not uniform. The maximum velocity occurs at **0.05–0.25 y below the surface**. Mean velocity ≈ velocity at **0.6 y depth** (from the surface), or the average of the velocities at 0.2y and 0.8y. Surface velocity × 0.8–0.95 ≈ mean velocity.

KEY FORMULAE – UNIFORM FLOW

- **Chezy**: $V = C\sqrt{(R\,S)}$
- **Manning**: $V = (1/n)\,R^{2/3}\,S^{1/2}$; relation $\mathbf{C = R^{1/6}/n}$
- Other C formulae: Bazin C = 87/(1 + K/√R); Ganguillet - Kutter
- Typical n: smooth concrete 0.012–0.013; brick 0.015; earth channel in good condition 0.020–0.025; natural rivers 0.030–0.040
- Conveyance $K = (1/n)AR^{2/3}$, so $Q = K\sqrt{S}$. Section factor for uniform flow = $AR^{2/3}$.

Most economical (efficient) section	Condition	Hydraulic radius
Rectangular	**b = 2y** (width = twice depth)	**R = y/2**
Trapezoidal	Half-hexagon: sides at **60° to horizontal** (n = 1/√3). Half the top width = sloping side length. For a given side slope n: b + 2ny = 2y√(1 + n²).	**R = y/2**
Triangular	Vertex angle **90°** (sides at 45°)	R = y/(2√2)
Circular, max velocity	Depth = **0.81 D** (θ ≈ 257.5°)	R ≈ 0.304 D
Circular, max discharge	Depth = **0.938 D** (Manning); 0.95 D (Chezy)	—

- The best hydraulic section has **minimum wetted perimeter for a given area**, which means maximum R and maximum Q. The theoretical best of all is the semicircle; the half-hexagon is the best trapezoid.
- A circular conduit running **full** carries less than its maximum discharge (≈ 0.93 times the maximum). Its velocity when full equals the velocity when half-full.
- **Specific energy** $E = y + V^2/2g = y + q^2/(2gy^2)$. This is energy measured from the **channel bed**.
- For a given E there are two **alternate depths**: a **subcritical** one ($y > y_c$) and a **supercritical** one ($y < y_c$).
- **Critical flow** = **minimum specific energy for a given q**, which is the same as **maximum q for a given E**. The **specific force** is also a minimum there, and Fr = 1.



Specific energy curve (constant q). The upper limb is asymptotic to E = y and the lower limb to the E-axis; C = critical point. y_1 and y_2 are the alternate depths for the same E.

KEY FORMULAE – CRITICAL FLOW & JUMP

- Rectangular channel: $\mathbf{y_c = (q^2/g)^{1/3}}$; $\mathbf{E_c = 1.5\,y_c}$ ($y_c = 2E_{min}/3$); $V_c = \sqrt{(g\,y_c)}$; velocity head at critical = $y_c/2$
- General section: $\mathbf{Q^2T/(gA^3) = 1}$. Triangular channel: E_c = **1.25 y_c**. Parabolic channel: $E_c = (4/3)\,y_c$.
- **Froude number** Fr = V/√(gD), with D = hydraulic depth. Fr < 1 subcritical (tranquil, streaming); Fr = 1 critical; Fr > 1 supercritical (rapid, shooting).
- Celerity of a small gravity wave $c = \sqrt{(gy)}$. In subcritical flow disturbances travel upstream; in supercritical flow they cannot.
- **Hydraulic jump, sequent (conjugate) depths**: $\mathbf{y_2/y_1 = ½[-1 + \sqrt{(1 + 8Fr_1^2)}]}$; also $y_1y_2(y_1 + y_2) = 2q^2/g$
- **Energy loss in the jump**: $\mathbf{\Delta E = (y_2 - y_1)^3/(4\,y_1\,y_2)}$
- Height of the jump = $y_2 - y_1$; length ≈ **5 to 7 ($y_2 - y_1$)** (≈ 6.9 ($y_2 - y_1$))
- **Specific force** $M = Q^2/(gA) + A\,\bar{z}$ ($\bar{z}$ = depth of centroid). It is **conserved across a jump**, while specific energy is lost.

Fr_1 (approach)	Type of jump (USBR)	Energy loss

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1.0–1.7	**Undular** jump	< 5%
1.7–2.5	Weak jump	5–15%
2.5–4.5	**Oscillating** jump (unstable; avoid)	15–45%
4.5–9.0	**Steady** jump (best for stilling basins)	**45–70%**
> 9.0	**Strong** jump	70–85%

- A hydraulic jump always takes flow from **supercritical to subcritical**, never the other way. Uses: **energy dissipation** below spillways and sluices, raising the water level for irrigation, mixing coagulants in water treatment, aeration, and removing air pockets from pipelines.
- A **hump** on the bed (or a **width contraction**) causes the water surface to **fall** in subcritical flow and **rise** in supercritical flow. If the hump is higher than ($E_1 - E_c$), the flow is **choked** and the upstream depth rises (afflux).
- **Venturi flume** = a throat contraction (critical-depth meter). **Parshall flume** = a standing-wave flume with a converging section, a **throat with a downward-sloping floor** and a diverging section. It needs only **one head reading** (upstream) under free flow, has a small head loss and is **self-cleaning**. It is used for irrigation canals and the inlets of sewage treatment plants.
- **Surges** (moving hydraulic jumps): a **positive surge** raises the depth (sudden closure of a gate downstream; a tidal bore). A **negative surge** lowers it (sudden gate opening).

KEY FORMULAE – GVF

- **$dy/dx = (S_0 - S_f)/(1 - Fr^2)$**
- Methods of computing profiles: direct step (prismatic channels), standard step (natural channels), graphical integration, Bresse's method

Slope class	Condition	Profiles	Typical occurrence
Mild (M)	$y_n > y_c$	M1, M2, M3	**M1 = backwater behind a dam or weir** (the longest profile); M2 = drawdown approaching a free overfall or a change to a steep slope; M3 = flow below a sluice gate on a mild slope (followed by a jump)
Steep (S)	$y_c > y_n$	S1, S2, S3	S1 = behind an obstruction on a steep slope (starts with a jump); S2 = just below a break from mild to steep slope; S3 = below a sluice on a steep slope
Critical (C)	$y_n = y_c$	C1, C3	Rare
Horizontal (H)	$S_0 = 0$, $y_n = \infty$	H2, H3	Free fall at the end of a horizontal bed; below a sluice
Adverse (A)	$S_0 < 0$	A2, A3	Rising bed

- There are **12** possible GVF profiles in total. Zone 1 (y above both y_n and y_c) and zone 3 (y below both) profiles have a **rising** water surface (dy/dx > 0). Zone 2 profiles are **drawdown** curves (dy/dx < 0).
- GVF profiles approach normal depth **asymptotically** and meet the critical-depth line at **right angles** (in theory).
- **Afflux** = the maximum rise of the water surface upstream of an obstruction (a weir or bridge piers).

MEMORY TRICK

"**M-1 Mountain behind the Dam**" means the backwater is M1. **Economical rectangle: "Twice as wide as deep, R = half depth."** Circular pipe: "**81 for speed, 94 for flow**" (0.81D, 0.938D).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Most economical rectangular channel? → **b = 2y, R = y/2.**
- Minimum specific energy in a rectangular channel? → **1.5 y_c.**
- Energy loss in a hydraulic jump? → **$(y_2 - y_1)^3/4y_1y_2$.**
- Type of jump for Fr_1 = 4.5–9? → **Steady jump.**
- Backwater curve behind a dam on a mild slope? → **M1.**
- Depth for maximum discharge in a circular channel (Manning)? → **0.938 D.**

7.9 Hydraulic Machines ★★☆

- **Turbine** converts hydraulic energy into mechanical energy. A **pump** converts mechanical energy into hydraulic energy.
- **Impulse turbine**: all the available head is converted into kinetic energy in a **nozzle**. The runner works at **atmospheric pressure** and need not run full. Example: **Pelton wheel**.
- **Reaction turbine**: part of the energy is pressure energy at runner entry. The runner is **enclosed and runs full**, and a draft tube is fitted. Examples: **Francis, Kaplan, propeller**.
- Specific speed of a turbine: **$N_s = N\sqrt{P}/H^{5/4}$** (P in kW or metric hp). It is the speed of a geometrically similar turbine producing **1 kW (or 1 hp) under 1 m head**.
- **Unit quantities** (under unit head): $N_u = N/\sqrt{H}$, $Q_u = Q/\sqrt{H}$, $P_u = P/H^{3/2}$. They are used to predict performance under a different head.
- Efficiencies: **hydraulic** = power given to the runner / water power (ρgQH); **mechanical** = shaft power / runner power; **overall = $\eta_h \times \eta_m$.**

Turbine	Type / flow	Head	N_s (SI, kW)	Notes

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Pelton wheel	**Impulse**, tangential flow	**High (> 250 m)**	**8.5–30** (single jet); up to ≈ 50 multi-jet	Buckets with a splitter, deflecting about **165°**. Max efficiency at u ≈ V/2 (actually 0.46 V). Jet ratio m = D/d ≈ 12 (11–14). Number of buckets z = 15 + D/2d.
Francis	**Reaction, mixed (radial inward)** flow	**Medium (30/60–250 m)**	**50–300**	Guide vanes (wicket gates); the most widely used turbine. Modern Francis is mixed flow.
Kaplan	**Reaction, axial** flow	**Low (< 30 m)**	**250–1000**	**Adjustable runner blades** (double regulated), so efficiency stays high at part load. 3–8 blades.
Propeller	Reaction, axial	Low	300–1000	Fixed blades; poor part-load efficiency.
Deriaz	Reaction, diagonal	Medium-low	—	Adjustable blades; used as a reversible pump-turbine.

- Ranges of N_s and head differ between textbooks. The **order** never changes: Pelton (lowest N_s, highest head) < Francis < Kaplan (highest N_s, lowest head).
- **Governing**: the Pelton wheel uses a **spear (needle) valve plus a jet deflector**, which avoids water hammer. Francis turbines use **wicket gates**. Kaplan turbines use wicket gates **and** runner blades.
- **Draft tube** (reaction turbines only): a diverging tube from the runner exit to the tailrace. It (1) **converts exit kinetic energy into pressure energy**, recovering head, and (2) allows the turbine to be placed **above the tailrace** without losing head. Types: **conical** (η ≈ 90%, cone half-angle ≤ 8°), Moody spreading, simple elbow (≈ 60%), elbow with circular inlet and rectangular outlet. The draft tube outlet must stay **submerged** in the tailrace.
- Penstock = the pipe carrying water from the forebay or surge tank to the turbine. The tailrace carries water away after the turbine.
- **Cavitation in turbines** occurs at the runner outlet and draft tube inlet (lowest pressure). **Thoma's cavitation factor $\sigma = (H_{atm} - H_v - H_s)/H$**, where H_s = height of the runner exit above the tailrace. Cavitation is avoided when **$\sigma > \sigma_c$** (critical). The cure is to set the runner lower (reduce H_s) and use stainless steel or cavitation-resistant materials.
- **Centrifugal pump**: works on the **forced vortex** principle. Parts: impeller (usually with **backward-curved vanes**), casing (**volute**, vortex, or **diffuser** with guide blades), suction pipe with a **foot valve and strainer**, and a delivery pipe with a valve.
- **Priming** = filling the suction pipe, casing and part of the delivery pipe with the liquid to **expel air**. It is needed because the head developed depends on density, and air at the impeller produces negligible pressure. Self-priming and submersible pumps do not need it.
- Impellers: **closed** (clean water), semi-open, **open/non-clog** (sewage and liquids with solids).
- **Manometric head H_m** = the head the pump must actually produce (static lift + losses + exit velocity head). **Manometric efficiency $\eta_{mano} = g H_m/(V_{w2} u_2)$**. Overall efficiency $\eta_o = \rho g Q H_m$ / shaft power.
- Euler head (radial entry, $V_{w1} = 0$): $H = V_{w2}u_2/g$. Minimum starting speed condition: $u_2^2 - u_1^2 \geq 2gH_m$.
- Specific speed of a pump: **$N_s = N\sqrt{Q}/H^{3/4}$**. It is the speed of a geometrically similar pump delivering **1 m³/s against 1 m head**. Radial (centrifugal) pumps have low N_s, mixed-flow pumps medium, axial pumps the highest.
- **Affinity laws** for geometrically similar pumps: **$Q \propto N D^3$, $H \propto N^2D^2$, $P \propto N^3D^5$**. For one pump at a changed speed: $Q \propto N$, $H \propto N^2$, $P \propto N^3$.
- **Multistage pumps**: impellers **in series** give **high head** (heads add, same Q). Pumps **in parallel** give **large discharge** (discharges add, same H).
- **NPSH (net positive suction head)** = $H_{atm} - H_v - h_s - h_{fs}$, where h_s = suction lift. To avoid cavitation, **NPSH available > NPSH required**. The theoretical maximum suction lift is 10.3 m; in practice it is about **6–7 m**.
- **Characteristic curves**: main (constant speed), operating, and **muschel (iso-efficiency)** curves.

Item	Centrifugal pump	Reciprocating pump
Principle	Centrifugal action (forced vortex)	**Positive displacement** (piston)
Suited to	**Large discharge**, moderate head	**Small discharge, high head**
Flow	Continuous, uniform	Pulsating (smoothed by air vessels)
Priming	Required	Not required
Viscous liquids / sewage	Suitable	Not suitable
Starting	Delivery valve **closed** (minimum power at zero flow)	Delivery valve **open**

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KEY FORMULAE – RECIPROCATING PUMP

- Theoretical discharge: single-acting $\mathbf{Q_{th} = A\,L\,N/60}$; double-acting $Q_{th} = 2ALN/60$ (neglecting the piston rod)
- **Slip** = $Q_{th} - Q_{act}$; % slip = $(1 - C_d) \times 100$. **Negative slip** ($Q_{act} > Q_{th}$) occurs with a long suction pipe, a short delivery pipe and high speed, because the delivery valve opens before the suction stroke ends.
- Acceleration head $h_a = (L/g)(A/a)\,\omega^2 r \cos\theta$ (maximum at the start and end of a stroke)

- **Air vessel**: a closed chamber fitted close to the cylinder on the suction and delivery sides. It gives a **continuous and uniform** flow, reduces the acceleration head, allows **higher speeds**, prevents separation, and **saves power**: about **84.8%** of the friction work in a single-acting pump and **39.2%** in a double-acting pump.
- Indicator diagram: the area ∝ work done per stroke. Separation in the suction pipe begins when the pressure head falls to about 2.5 m of water absolute.
- Other machines: **hydraulic ram** (uses **water hammer** to lift a small quantity to a large height without external power), hydraulic press and jack (Pascal's law), hydraulic accumulator (stores energy), intensifier (raises pressure), jet pump, air-lift pump (for deep wells), gear pump (oil).

MEMORY TRICK

"**P-F-K = High-Medium-Low head**" and "**Low-Medium-High N_s**". The impulse turbine is the Pelton, which works at atmospheric Pressure. Turbine N_s uses **P** (power out) and pump N_s uses **Q** (water out).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Turbine suited to very high head? → **Pelton wheel (impulse)**.
- Kaplan turbine is which type? → **Axial-flow reaction turbine with adjustable blades**.
- Draft tube is used in which turbines? → **Reaction turbines**.
- Specific speed of a pump? → $N\sqrt{Q}/H^{3/4}$.
- Pumps connected in series give? → **Higher head at the same discharge**.
- Power saved by fitting an air vessel to a single-acting reciprocating pump? → **84.8%**.

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8. Hydrology & Irrigation Engineering

> **NOTE**
>
> This exam's CWC is the **Central Warehousing Corporation**. Do not confuse it with the **Central Water Commission** (also "CWC"), the hydrology/water-resources body covered in 8.9. Questions in SSC JE / AE papers keep coming back to a few areas: rain-gauge density and mean rainfall methods, φ-index, unit hydrograph and S-curve, Dicken's and Ryves' formulae, duty–delta, Lacey's equations, Bligh, Lane and Khosla, the elementary profile of a gravity dam, and cross-drainage works. Learn the formulae and their units first.

8.1 Hydrologic Cycle & Precipitation ★★★

- **Hydrologic cycle** = the continuous circulation of water: evaporation → condensation → precipitation → interception → infiltration → runoff → back to the sea. It has **no beginning and no end**, and the **sun** drives it.
- **Water budget equation** (for a catchment over a period Δt): **P − R − G − E − T = ΔS**. Here P = precipitation, R = surface runoff, G = net groundwater outflow, E = evaporation, T = transpiration and ΔS = change in storage.
- **Rainfall–runoff form**: R = P − L, where L = all losses (abstractions).
- A **catchment** is also called a **watershed**, **drainage basin** or **river basin**. The **ridge line** that divides two catchments is the **water divide**.
- For precipitation to form you need moist air to be lifted and cooled, **condensation nuclei** (salt, dust, smoke) and drops that grow large enough. **Cloud seeding** uses **silver iodide** or dry ice in cold clouds and common salt in warm clouds.

Form of precipitation	Key fact
Rain	Drop size **> 0.5 mm**, up to about 6 mm. Intensity: light **< 2.5 mm/h**, moderate 2.5–7.5 mm/h, heavy **> 7.5 mm/h**
Drizzle	Drops **< 0.5 mm**, intensity < 1 mm/h
Glaze	Rain or drizzle that **freezes on contact** with cold ground
Sleet	Frozen raindrops (ice pellets) that fall through air below 0 °C
Snow	Ice crystals; density about **0.1 g/cc**
Hail	Ice balls **> 8 mm** formed in violent thunderstorms (cumulonimbus)

Type (by lifting mechanism)	Cause	Character / example
Convective	Local heating → warm air rises	Short and very intense; tropical summer thunderstorms
Orographic	Moist air forced up by **mountain barriers**	The **most important type in India**. Heavy rain on the windward side (Western Ghats, NE hills); **rain shadow** on the leeward side
Cyclonic (frontal / non-frontal)	Air lifted by convergence into a low-pressure area, or along a warm/cold front	Wide-spread, long duration; tropical cyclones on the east coast

Rain gauges

Gauge	Type	Key facts
Symon's gauge	Non-recording	The standard non-recording gauge in India: funnel of **127 mm (5 in)** diameter with a collecting bottle. Read daily at **08:30 IST**. IMD now uses FRP gauges with **100 cm² and 200 cm²** collector areas (**IS 5225:1992**). Rim is about **30 cm above ground**
Tipping bucket	Recording	Each tip = **0.25 mm** of rain. Gives an electrical pulse, so it suits **telemetry** and remote stations
Weighing bucket	Recording	Records the **cumulative mass curve** of rainfall; also records snow and hail
Natural siphon (float) type	Recording	The **standard recording gauge of IMD**. A float drives a pen; the chamber empties by siphon. Gives the mass curve

- **Siting**: level open ground, at a distance of at least **twice the height of the nearest obstruction**, and fenced.
- **Recording gauges** are also called **self-recording**, **automatic** or **integrating** gauges. They give **intensity and duration**; a non-recording gauge gives **only the total depth**.
- **Weather radar** estimates areal rainfall up to about 200 km away.

Rain-gauge density (IS 4987:1994)	One gauge per
Plains	**520 km²**
Elevated regions (average elevation ≈ 1000 m)	**260–390 km²**
Predominantly hilly areas with heavy rainfall	**130 km²**
Recording gauges	At least **10%** of all gauges should be self-recording

- **WMO norms**: flat temperate or tropical regions 600–900 km² per gauge; mountainous regions 100–250 km²; arid and polar regions 1500–10,000 km².

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KEY FORMULAE

- **Optimum number of rain gauges**: $N = (C_v/\varepsilon)^2$. $C_v = 100\ \sigma_{m-1}/\bar{P}$ is the coefficient of variation (%) of the existing m gauges; ε = allowable % error, usually **10%**. $\sigma_{m-1} = \sqrt{[\Sigma(P_i - \bar{P})^2/(m-1)]}$.
- **Missing data**, arithmetic mean method: $P_x = (P_1 + P_2 + \ldots + P_M)/M$. Use it when the normal annual rainfall N of each index station is within **10%** of N_x.
- **Missing data**, normal ratio method: $P_x = (N_x/M)\ \Sigma\ (P_i/N_i)$. Use it when any N_i differs from N_x by **more than 10%**.
- **Thiessen polygon**: $\bar{P} = \Sigma\ P_iA_i/\Sigma A_i$. A_i is the polygon area, bounded by the **perpendicular bisectors** of the lines joining the stations.
- **Isohyetal**: $\bar{P} = \Sigma\ [A_i\ (P_i + P_{i+1})/2]\ /\ \Sigma A$. A_i is the area between consecutive isohyets.
- **Double mass curve** correction: $P_{cx} = P_x \times (M_c/M_a)$. M_c = slope of the corrected (original) period and M_a = slope of the period being adjusted.
- **DAD (Horton)**: $\bar{P} = P_0 \exp(-K\ A^n)$. The average depth **decreases as area increases** and increases with duration.
- **IDF**: $i = K\ T^x/(D + a)^n$. Intensity **decreases with duration** and **increases with return period**.
- **PMP (Hershfield, statistical)**: PMP = $\bar{P}$ + K σ, with **K ≈ 15**.

Mean areal rainfall method	Weightage	Remark
Arithmetic mean	Equal	Flat area with uniformly spaced gauges; **least accurate**
Thiessen polygon	By area of the polygon	Objective and mechanical; **ignores orography**. A **new polygon network** is needed whenever a gauge is added or lost
Isohyetal	Area between isohyets	**Most accurate**; accounts for orography; needs skill

- A **double mass curve** tests the **consistency** of a record. You plot the accumulated rainfall of the station against the accumulated mean of a group of base stations. A **break in slope** shows an inconsistency, caused by a shifted gauge, changed exposure or an observation error.
- A **mass curve of rainfall** plots **accumulated rainfall against time**. Its slope at any point is the intensity. A **hyetograph** is a **bar chart of intensity against time**.
- **PMP** = the greatest depth of precipitation that is physically possible for a given duration over a given area. It is used to derive the **PMF** for spillways of major dams.
- **Isohyet** = a line of equal rainfall. **Mawsynram and Cherrapunji** (Meghalaya) are among the wettest places in the world. India's average annual rainfall is about **1170 mm**.

MEMORY TRICK

Rain-gauge density "**520 – 390 – 130**": plain ground gets the fewest gauges and hills get the most. 130 = 520 ÷ 4.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Standard recording rain gauge used by IMD? → **Natural siphon (float) type**.
- Consistency of a rainfall record is checked by? → **Double mass curve**.
- Most accurate method of mean areal rainfall? → **Isohyetal method**.
- C_v = 30%, ε = 10%: optimum number of gauges? → $N = (30/10)^2$ = **9**.
- Missing rainfall when normals differ by more than 10%? → **Normal ratio method**.
- Rain gauge density in plains as per IS 4987? → **1 per 520 km²**.

8.2 Abstractions: Evaporation, Infiltration & Runoff ★★☆

Evaporation & evapotranspiration

- **Dalton's law**: $E = C\ (e_w - e_a)$. Evaporation is proportional to the difference between the saturation vapour pressure at the water temperature (e_w) and the actual vapour pressure of the air (e_a).
- **Meyer's formula**: $E_L = K_M(e_w - e_a)(1 + u_9/16)$ mm/day. e is in mm of Hg and u_9 = wind speed (km/h) at 9 m height. K_M = **0.36** for large deep water bodies and **0.50** for small shallow ones.
- Evaporation **increases** with water temperature, wind speed and the vapour-pressure deficit. It **decreases** with atmospheric pressure, salinity and humidity. It is about **2–3% less for sea water**.
- **Reducing reservoir evaporation**: a monomolecular film of **cetyl alcohol (hexadecanol)** reduces losses by about 20–40%. Wind breaks and floating covers also help.
- **Lake evaporation = C_p × pan evaporation**, because a pan evaporates more than a lake. The pan coefficient C_p is therefore < 1.

Pan	Size	Pan coefficient
Class A (US Weather Bureau)	1210 mm dia × 255 mm deep, on a wooden platform 150 mm above ground	**0.70**
ISI standard pan (modified Class A, **IS 5973**)	1220 mm dia × 255 mm deep, copper sheet, covered with **hexagonal wire mesh**	**0.80**
Colorado sunken pan	920 mm square × 460 mm deep, sunk into the ground	0.78
USGS floating pan	900 mm square × 450 mm deep, floats in the lake	0.80

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- **Transpiration** = water lost through the leaves (stomata). **Evapotranspiration (ET)**, also called **consumptive use**, is evaporation plus transpiration.
- **PET** is the ET when water supply is **unlimited**, with a short green crop covering the ground completely. **AET ≤ PET**, and AET = PET only when water is not limiting.
- **Lysimeter** = a soil-filled tank with a crop growing in it. It gives a **direct measurement** of ET by water balance.
- **Blaney–Criddle**: $C_u = k \Sigma\, p(1.8t + 32)/40$ in cm. k = crop coefficient, t = mean monthly temperature (°C), p = monthly % of annual daytime hours. Needs only temperature data, so it is suited to **arid** regions.
- **Penman**: combines the **energy balance** and the **aerodynamic (mass transfer)** approaches. PET = $(AH_n + E_a\gamma)/(A + \gamma)$. It is the most accurate of the empirical methods. FAO now uses Penman–Monteith.
- **Thornthwaite**: PET = $1.6\, L_a(10\, T/I_t)^a$ cm/month; temperature-based. **Hargreaves** is a pan-based method.
- **Interception** = rain held by vegetation. **Depression storage** = water held in surface depressions.

Infiltration

- **Infiltration capacity f_p** = the maximum rate at which a soil can absorb water. Actual rate f = f_p if i ≥ f_p; f = i if i < f_p.
- **Horton's equation**: $f_p = f_c + (f_0 - f_c)\, e^{-k_h t}$. f_0 = initial capacity and f_c = final steady capacity. Other models: **Philip** $F = s\, t^{½} + K\, t$, and **Green–Ampt**.
- Infiltration is affected by soil type, moisture content (wet soil gives lower f), vegetation, compaction, temperature (water viscosity), entrapped air and the quality of the water.
- **Flooding-type infiltrometers**:
  - **Single ring**: about 30 cm dia, 60 cm long, driven about 50 cm into the ground.
  - **Double ring**: rings of 30 and 60 cm. The **outer ring acts as a buffer** against lateral spread, so the inner ring gives a better reading.

  Rainfall simulators give values lower than flooding types.
- **φ-index** = the **constant rate of loss** above which the rainfall volume equals the runoff volume. It includes initial losses.
- **W-index** = $(P - R - I_a)/t_e$. It excludes initial losses, so **W-index ≤ φ-index**. W_{min}-index = the W-index for very wet conditions ≈ φ.

KEY FORMULAE

- **Rational method**: $Q_p = C\, i\, A / 3.6$, with Q in m^3/s, i in mm/h and A in **km²**. With A in **hectares**: $Q_p = C\, i\, A / 360$.
- In the rational method, i = intensity for a duration equal to the **time of concentration t_c**. It is used for **small catchments** (urban drains, culverts): about **< 50 km²** in most texts, some say < 25 km².
- Weighted $C = \Sigma C_i A_i / \Sigma A_i$.
- **Kirpich**: t_c (min) = $\mathbf{0.01947\, L^{0.77}\, S^{-0.385}}$, with L = maximum flow length in m and S = average slope (m/m).
- **SCS-CN**: $Q = (P - 0.2S)^2/(P + 0.8S)$ for P > 0.2S, with S = 25400/CN − 254 (mm). CN ranges 0–100; CN = 100 means fully impervious.
- **Khosla's monthly runoff**: $R_m = P_m - L_m$, with $L_m = 0.48\, T_m$ (cm; T_m in °C > 4.5 °C).
- **Inglis–DeSouza** (Western Ghats): R = 0.85P − 30.5. Deccan plateau: R = P(P − 17.8)/254 (cm).

Surface	Runoff coefficient C
Roofs, concrete/asphalt pavement	**0.70–0.95**
Gravel roads	0.35–0.70
Lawns and parks (sandy soil)	0.05–0.20
Forest	0.10–0.20

- **Runoff components**:
  - **Surface runoff** (overland flow plus channel flow).
  - **Interflow** (subsurface flow): prompt interflow is grouped with direct runoff.
  - **Base flow** (groundwater flow).

  Direct runoff = surface runoff + prompt interflow.
- **Streams**:
  - **Perennial**: flows all year; an **effluent** stream that receives groundwater.
  - **Intermittent**: flows in the wet season.
  - **Ephemeral**: flows only during and just after a storm; **no base flow** (arid areas).

  An **influent** stream loses water to the groundwater.
- **Factors affecting runoff**:
  - **Climatic**: rainfall type, intensity, duration, distribution, direction of storm movement, evaporation.
  - **Physiographic**: catchment size, shape, slope, orientation, land use, soil, drainage density.

  A **fan-shaped** catchment gives a **high, early peak**. A **fern-leaf (elongated)** catchment gives a low, late peak. A storm moving **downstream** gives a **higher peak**.
- **Drainage density** = total stream length ÷ catchment area. **Form factor** = A/L^2. **Compactness coefficient** = basin perimeter ÷ circumference of a circle of equal area.
- Empirical yield tables: **Strange's tables** (Maharashtra/Karnataka), **Barlow's tables** (UP), **Binnie's percentages** (MP).

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Stream gauging

Method	Key facts
Area–velocity	Q = Σ (area of segment × mean velocity). Most widely used
Current meter	Cup type (Price meter) or propeller type. Calibration: $v = aN_s + b$. Mean velocity is taken at **0.6 d** from the surface in shallow streams (d < about 3 m), or as the **average of 0.2 d and 0.8 d** in deeper streams
Float	Surface velocity × **0.85** ≈ mean velocity. Used in floods and for rough estimates
Dilution (chemical)	Constant-rate injection: $Q = Q_t(C_1 - C_2)/(C_2 - C_0)$. Suited to **turbulent mountain streams**, where the area–velocity method fails
Ultrasonic, electromagnetic, moving boat, slope–area	Indirect or modern methods. Slope–area uses Manning's equation and is used to estimate past flood peaks

- **Stage** = water-surface elevation above a datum, measured by a staff gauge, wire gauge, float gauge or bubble gauge.
- **Stage–discharge (rating) curve**: $Q = C_r(G - a)^{\beta}$, where a = stage at zero discharge. A **control** section makes the relation stable. The curve shows a **loop (hysteresis)** in unsteady floods: Q is higher on the rising stage than on the falling stage. Extrapolation is done by the **Running** or **logarithmic** method.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Pan coefficient of the Class A pan? → **0.70**. ISI pan? → **0.80**.
- Relation between W-index and φ-index? → **W ≤ φ**.
- Rational formula with A in hectares? → **Q = CiA/360**.
- Direct measurement of evapotranspiration? → **Lysimeter**.
- Single-point mean velocity in a shallow stream is taken at? → **0.6 depth below the surface**.
- Gauging of a turbulent, rocky mountain stream? → **Dilution method**.

8.3 Hydrographs & Floods ★★★

- **Hydrograph** = a plot of **discharge against time** at a section. Its parts:
  - **Rising limb** (concentration curve).
  - **Crest segment** (peak).
  - **Recession (falling) limb**, which depends **only on catchment storage** and not on the storm. Recession equation: $Q_t = Q_0 K_r^{\,t}$.
- **Basin lag (t_p)** = time from the centroid of the effective rainfall to the peak. **Time of concentration** = time for water from the most remote point to reach the outlet. It equals the time from the end of effective rainfall to the **inflection point** on the recession limb.
- **Base-flow separation**: the straight-line method, the N-day method (**$N = 0.83\,A^{0.2}$ days**, A in km²; $N = A^{0.2}$ with A in sq. miles) and the concave method.
- **ERH** (effective rainfall hyetograph) = rainfall excess. Its volume equals the **DRH** (direct runoff hydrograph) volume.

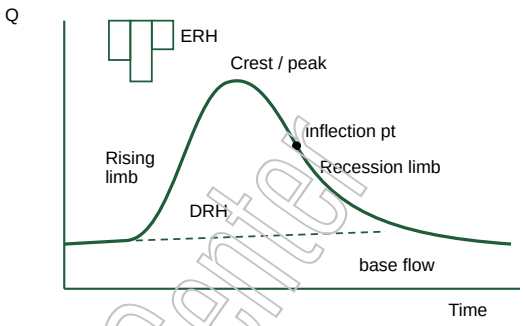

Fig 8.1 Single-peaked storm hydrograph. The dashed line separates base flow from direct runoff (DRH).

Unit hydrograph (Sherman, 1932)

- **D-h UH** = the DRH produced by **1 cm** of effective rainfall, falling uniformly over the basin at a uniform rate for D hours.
  - Area under the UH = **catchment area × 1 cm**.
  - Check: $\Sigma Q \cdot \Delta t\ (m^3) = A\ (m^2) \times 0.01$.
- **Assumptions**:
  - **Time invariance**.
  - **Linear response**, i.e. the principles of **proportionality** and **superposition**.
  - The same time base for all storms of duration D.
- **Limits of use**: catchments up to about **5000 km²**; larger basins are split into sub-basins. Not valid for snowmelt runoff.
- **Derivation**: pick an isolated single-peaked storm of about duration D. Subtract base flow to get the DRH. Divide the DRH ordinates by the runoff depth in cm to get the UH.
- **Changing the duration**:
  - If the new duration is an integer multiple (nD), add n lagged UHs and divide by n.
  - Otherwise use the **S-curve** (summation curve). It is the hydrograph produced by continuous effective rainfall at **1/D cm/h**, and its **equilibrium discharge** is Q_s = **2.778 A/D** m³/s (A km², D h).
  - T-h UH ordinate = $(S_t - S_{t-T}) \times D/T$.
- **IUH** (instantaneous UH) is the limiting case D → 0. Models: Nash (n linear reservoirs) and Clark.
- **Synthetic UH (Snyder, 1938)**, for ungauged basins:
  - Basin lag $t_p = C_t(L \cdot L_{ca})^{0.3}$ h. L = main stream length and L_{ca} = distance to the point nearest the basin centroid (km); C_t ≈ 1.35–1.65.
  - Standard rainfall duration $t_r = t_p/5.5$.
  - Peak $Q_p = 2.78\,C_p A/t_p$, with C_p ≈ 0.56–0.69.

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CWC's regional Flood Estimation Reports use similar synthetic-UH relations.

Flood estimation

Formula (Q in m^3/s, A in km^2)	Region / constants
Dicken's: $Q = C_D A^{3/4}$	North & central India. C_D: north Indian plains **6**; north Indian hills 11–14; central India 14–28; coastal Andhra & Odisha 22–28
Ryves': $Q = C_R A^{2/3}$	Tamil Nadu and south India. C_R = **6.8** within 80 km of the east coast; **8.5** for 80–160 km; **10.2** for limited areas near hills
Inglis: $Q = 124 A/\sqrt{(A + 10.4)}$	**Fan-shaped** catchments of old **Bombay State (Maharashtra)**
Rational method	Small catchments (see 8.2)

- **Methods of flood estimation**: empirical formulae, envelope curves, the rational method, unit hydrograph, and **flood frequency analysis** (Gumbel, log-Pearson Type III, log-normal).

KEY FORMULAE – FREQUENCY & ROUTING

- Probability of exceedance in any one year: **p = 1/T**. Non-exceedance probability q = 1 − p.
- **Risk** (the event occurs at least once in n years): **$R = 1 - (1 - 1/T)^n$**. **Reliability** = $(1 - 1/T)^n$.
- Probability of exactly r occurrences in n years: ${}^nC_r\, p^r\, q^{n-r}$ (binomial).
- **Plotting position** (data in descending order, rank m, N years): **Weibull** P = m/(N + 1), so T = (N + 1)/m. California P = m/N; Hazen P = (2m − 1)/2N.
- **Gumbel**: $x_T = \bar{x} + K\sigma_{n-1}$, with $K = (y_T - \bar{y}_n)/S_n$ and reduced variate $y_T = -\ln[\ln(T/(T - 1))]$. For an infinite sample, $\bar{y}_n \approx 0.577$ and $S_n = 1.2825$, which gives $K_{100} \approx 3.14$.
- **Continuity (storage) equation**: $I - Q = dS/dt$.
- **Muskingum**: $S = K[xI + (1 - x)Q]$. K = storage time constant (≈ travel time through the reach); x = weighting factor of **0–0.5** (≈ 0.2–0.3 for natural rivers).
  - Routing equation: $Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_1$, with **$C_0 + C_1 + C_2 = 1$**.
  - $C_0 = (0.5\Delta t - Kx)/(K - Kx + 0.5\Delta t)$; $C_1 = (0.5\Delta t + Kx)/(K - Kx + 0.5\Delta t)$; $C_2 = (K - Kx - 0.5\Delta t)/(K - Kx + 0.5\Delta t)$.
  - Choose $2Kx < \Delta t < K$.

- **Flood routing** = finding the outflow hydrograph from a known inflow hydrograph.
  - **Reservoir (level-pool) routing**: modified **Puls**, Goodrich, **ISD** (inflow–storage–discharge) and Coefficient methods.
  - **Channel routing**: **Muskingum** (hydrologic). Hydraulic routing uses the St. Venant equations.
- **Reservoir effect**: **attenuation** (peak reduced) and **lag**. For an uncontrolled spillway, the outflow peak occurs where the **outflow hydrograph cuts the falling limb of the inflow** (I = Q at that instant), and that is also the moment of maximum storage.
- **Muskingum limits**: x = 0 means a linear reservoir (storage depends on outflow only, maximum attenuation). **x = 0.5** means **pure translation** with no attenuation.
- **Design floods**: **PMF** = flood from PMP on critical catchment conditions. **SPF** = from the most severe storm considered reasonably characteristic of the region; SPF ≈ 40–60% of PMF.

Dam size (IS 11223:1985)	Gross storage / hydraulic head	Inflow design flood
Small	0.5–10 Mm^3 or 7.5–12 m	**100-year flood**
Intermediate	10–60 Mm^3 or 12–30 m	**SPF**
Large	> 60 Mm^3 or > 30 m	**PMF**

CODE UPDATE

CWC's 2021 *Guidelines for Selecting and Accommodating Inflow Design Floods for Dams*, issued under the Dam Safety framework, link the design flood to the **hazard potential** of the dam, not just its size. The IS 11223 table above is still what MCQs usually test.

MEMORY TRICK

"**Dicken's ¾ – Ryves ⅔**": D comes before R, and ¾ is bigger than ⅔. Dicken's is for the North, Ryves for the South (Tamil Nadu). For Muskingum, "x = **half** means no attenuation at all."

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Area under a unit hydrograph equals? → **1 cm of runoff over the catchment**.
- Risk that a 100-year flood occurs at least once in 100 years? → $1 - 0.99^{100} \approx$ **63%**.
- Exponent of A in Dicken's formula? → **3/4**.
- Muskingum x for pure translation? → **0.5**.
- Spillway design flood for a large dam? → **PMF**.
- Equilibrium discharge of the S-curve? → **2.778 A/D** m^3/s.

8.4 Groundwater Hydrology ★★☆

Formation	Stores water?	Transmits?	Example
Aquifer	Yes	Yes (readily)	Sand, gravel
Aquitard	Yes	**Slowly** (leaky)	Sandy clay
Aquiclude	Yes (high porosity)	**No**	**Clay**
Aquifuge	No	No	**Solid granite**

- **Unconfined (water-table / phreatic) aquifer**: its upper surface is the water table at atmospheric pressure.
- **Confined (artesian) aquifer**: lies between impervious layers and is under pressure. Its water level is the **piezometric surface**. A well flows by itself (**flowing artesian well**) when the piezometric surface is above ground.

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- **Perched aquifer**: water held above a local impervious lens, above the main water table. **Leaky aquifer**: bounded by an aquitard.
- **Porosity n = S_y + S_r**, where S_y = specific yield (drains by gravity) and S_r = specific retention (held against gravity).
  - Clay: **high porosity** (45–55%) but **very low S_y** (1–5%).
  - Coarse sand: S_y ≈ 25–30%.
- **Storage coefficient (storativity) S** = volume of water released per unit surface area per unit decline of head.
  - Confined: S ≈ **5×10^{-5} to 5×10^{-3}**, from compression of the aquifer and expansion of the water.
  - Unconfined: S ≈ S_y (0.05–0.30).
- **Darcy's law**: v = k i and Q = kiA. It is valid for **laminar flow, Re < 1** (up to about 10). Seepage (actual) velocity = v/n.
- **Hazen's formula**: k = C D_{10}^2 with C ≈ 100 (k in cm/s, D_{10} in cm).
- **Transmissivity T = k b** (m^2/day), where b = aquifer thickness. It is the rate of flow through a unit-width strip of the full aquifer thickness under unit gradient.
- **Cone of depression** = the inverted cone-shaped drawdown surface around a pumped well. Its horizontal extent is the **radius of influence R** (typically 150–300 m). **Sichardt**: R = 3000 s√k (s in m, k in m/s).
- **Interference**: overlapping cones increase the drawdown and reduce the yield of each well.

KEY FORMULAE – STEADY RADIAL FLOW

- **Confined (Thiem)**: $Q = 2\pi kb(H - h_w)/\ln(R/r_w)$ = **$2.72\,T\,s_w/\log_{10}(R/r_w)$**. With two observation wells: $Q = 2\pi T(s_1 - s_2)/\ln(r_2/r_1)$.
- **Unconfined (Dupuit)**: $Q = \pi k(H^2 - h_w^2)/\ln(R/r_w)$ = **$1.36\,k(H^2 - h_w^2)/\log_{10}(R/r_w)$**.
- Dupuit's assumptions: flow is horizontal, the velocity is uniform over the depth, and the hydraulic gradient equals the slope of the water table.
- **Specific capacity** = Q/s_w (discharge per unit drawdown).
- **Jacob's drawdown**: $s_w = BQ + CQ^2$. BQ = formation (aquifer) loss and CQ^2 = **well loss**. Well efficiency = BQ/s_w.
- **Open-well recuperation test**: K/A = (2.303/T) $\log_{10}(s_1/s_2)$; yield Q = (K/A)·A·H. Typical K/A (per hour): clay **0.25**, fine sand **0.5**, coarse sand **1.0**.
- Unsteady flow: **Theis** s = (Q/4πT) W(u), with u = $r^2S/4Tt$. **Cooper–Jacob** is the straight-line approximation for small u (< 0.01).

Well type	Key facts
Open well (dug well)	Large diameter (1–10 m) and low yield; water enters through the bottom. A **shallow** well rests on a pervious layer. A **deep** well rests on an impervious "mota" layer and draws from the sandy layer below. **Working head** about 2.5–3 m; the **critical depression head** causes sand to boil (quick sand)
Tube well – strainer type	The most common type. Draws from several aquifers through strainers
Tube well – cavity type	Draws from below a strong clay (confined) layer. **No strainer**; water enters through a cavity at the bottom
Slotted / gravel-packed	Slotted pipe with a gravel envelope. Gives a higher yield in fine sand

MEMORY TRICK

"Aqui-**clude** ex**cludes** flow; aqui-**fuge flees** from water altogether." The unconfined (Dupuit) formula has **squares** ($H^2 - h^2$) and the constant 1.36. The confined (Thiem) formula is **linear** and uses 2.72, which is twice 1.36.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- A formation that is porous but impervious? → **Aquiclude (clay)**.
- Porosity is equal to? → **Specific yield + specific retention**.
- Unit of transmissivity? → **m^2/day**.
- The yield of an open well is tested by? → **Recuperation test**.
- Tube well without a strainer? → **Cavity type**.

8.5 Water Requirement of Crops ★★★

- **Duty (D)** = the area (ha) irrigated by **1 cumec** running continuously for the base period. Unit: **ha/cumec**.
- **Delta (Δ)** = total depth of water needed by the crop over the base period, in cm or m.
- **Base period (B)** = days from the **first watering** before sowing to the **last watering** before harvest. **Crop period** = sowing to harvesting. The crop period is slightly **more** than the base period, but they are usually taken as equal.
- **Duty increases downstream**, because losses are deducted along the way. Duty at the field (outlet) > at the head of the distributary > at the canal head.
- **Paleo** = the pre-sowing watering that wets the soil.
- **Kor watering** = the first watering after the plants are a few cm high. It needs the most water and is the critical one.
  - Kor depth: rice **19 cm**, sugarcane 16.5 cm, wheat **13.5 cm**.
  - Kor period: rice about 2–3 weeks; wheat 4 weeks (UP) to 8 weeks (Punjab).
- **Outlet factor** = duty at the outlet.
- **Command areas**:
  - **GCA** (gross command area) = the total area that can be irrigated.
  - **CCA** (culturable command area) = GCA minus unculturable area (roads, villages, ponds, barren land).
  - CCA divides into a cultivated part and a culturable but not cultivated part.

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- **Intensity of irrigation** = % of CCA proposed to be irrigated in a season. **Cropping intensity** can exceed 100% over the year.
- **Time factor** = days the canal actually runs ÷ days of the irrigation period. **Capacity factor** = mean supply ÷ full supply (design) discharge. Both are < 1.
- **Factors affecting duty**: crop type, climate, rainfall, soil type, base period, method of irrigation, canal conditions (losses), quality of water and the method of assessment. **Volumetric assessment** improves duty.
- **Improving duty**: canal lining, proper land preparation, crop rotation, efficient irrigation methods, volumetric charging and education of farmers.

KEY FORMULAE

- **$\Delta = 8.64\ B / D$**, with Δ in m, B in days and D in ha/cumec. (1 cumec × B × 86400 s spread over D × 10^4 m^2.)
- Equivalently Δ (cm) = 864 B/D.
- Design discharge at the head of a canal: Q = (CCA × intensity of irrigation)/outlet duty. Then divide by the time factor and add conveyance losses.
- **Depth of water stored** in the root zone: $d_w = (\gamma_d/\gamma_w) \times d \times (FC - m)$. d = root-zone depth and m = existing moisture content.
- **Frequency of irrigation** = d_w(readily available)/C_u (days).
- **Net irrigation requirement (NIR)** = C_u − effective rainfall. FIR = NIR/η_a. **GIR** = FIR/η_c.

Crop	Season	Typical Δ (Garg/Punmia)	Base period
Rice (paddy)	Kharif	**≈ 120 cm**	≈ 120 days
Sugarcane	Perennial (≈ 1 year)	**≈ 90 cm** (up to 120 cm in some texts)	**≈ 320 days**
Cotton	Kharif	≈ 50 cm	≈ 200 days
Wheat	Rabi	**≈ 40 cm**	≈ 120 days
Maize, jowar, bajra	Kharif	≈ 25–45 cm	≈ 100 days

- **Kharif** (monsoon, sown June–July, harvested Sept–Oct): rice, maize, jowar, bajra, cotton, groundnut, soybean, jute.
- **Rabi** (sown Oct–Nov, harvested Mar–Apr): wheat, barley, gram, mustard, peas, linseed.
- **Zaid** (Mar–June): watermelon, cucumber, moong.
- **Delta**: rice has the **highest Δ** among seasonal crops, so it has a **low duty**. Rabi crops have a lower Δ.

Soil moisture

Constant	Definition	Tension
Saturation	All pores full	0
Field capacity (FC)	Water held after free gravity drainage stops (2–3 days after irrigation)	**≈ 1/3 atm (0.33 bar)**
Permanent wilting point (PWP)	Plants can no longer extract water and wilt permanently	**≈ 15 atm (15 bar)**
Hygroscopic water	Thin film adsorbed on particles; not available to plants	≈ 31 atm

- **Available moisture** = FC − PWP (the root-zone storage plants can use).
- **Readily available moisture** ≈ **75%** of the available moisture (texts give 75–80%). Irrigation is given before moisture falls below the **optimum level**.
- **Gravitational water** (between saturation and FC) drains away and is **not available** to plants. **Capillary water** is the source for plants.
- **Consumptive use** = ET + water retained in plant tissue (about 1%).

Irrigation efficiencies

Efficiency	Formula
Conveyance η_c	Water delivered to fields ÷ water diverted from the source
Application η_a	Water stored in the root zone ÷ water delivered to the field
Storage η_s	Water stored in the root zone ÷ water needed to fill the root zone to FC
Distribution (uniformity) η_d	1 − ȳ/d. d = mean depth stored; ȳ = average deviation from the mean
Consumptive use efficiency	Normal consumptive use ÷ net water depleted from the root zone
Water-use efficiency	Crop yield ÷ water used

Method	Suitability / key fact
Free flooding	Cheapest and least efficient. For newly cleared or irregular land
Border strip	Strips 3–20 m wide, gentle slope (≈ 0.2–0.5%). For close-growing crops: wheat, fodder
Check / check basin	Level plots enclosed by bunds. For **rice**; most common in India
Basin (ring)	For **orchards** (one basin round each tree)
Furrow	For **row crops**: cotton, sugarcane, maize, potato. Only part of the surface is wetted
Sprinkler	For **undulating land, sandy soils** and shallow soils. Efficiency ≈ **70–80%**. Affected by wind; also gives frost protection
Drip (trickle)	Highest efficiency, **≈ 90%**. Emitters deliver 2–10 L/h. For orchards, vegetables, saline water and arid areas. Allows fertigation. Clogging is the main problem

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Sub-surface	Water applied below the surface through tiles or perforated pipes

MEMORY TRICK

"**Delta × Duty = 8.64 × Base**": read it as **DDB 864**. Duty **goes up as you go down** the canal, because the water still to be lost becomes less.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Base period 120 days, duty 864 ha/cumec: Δ? → 8.64 × 120/864 = **1.2 m**.
- Duty is expressed in? → **hectares per cumec**.
- Available moisture is the difference between? → **Field capacity and permanent wilting point**.
- Most efficient irrigation method? → **Drip irrigation**.
- First watering after the crop has grown a few cm? → **Kor watering**.

8.6 Canals, Silt Theories & Canal Structures ★★★

Alignment	Description	Cross-drainage works
Watershed / ridge canal	Runs along the ridge (watershed) and irrigates **both sides**	**Avoided** (drainages start from the ridge)
Contour canal	Follows a contour (hilly areas) and irrigates **one side only**	**Required** (crosses drainages)
Side-slope canal	Runs at right angles to the contours, roughly parallel to natural drainages	Not required, but the bed slope is steep (falls needed)

- **By function**: irrigation canal, **carrier canal** (also feeds another canal), **feeder canal** (only feeds another canal, irrigates nothing), navigation canal, power canal.
- **By discharge (hierarchy)**:
  - Main canal → branch canal (> 5 cumecs).
  - Major distributary (0.25–3 cumecs).
  - Minor distributary (< 0.25 cumec).
  - Watercourse / field channel.
- **Perennial** canals are fed from a weir or barrage or from a storage. **Inundation canals** draw directly from a river in flood, with no weir.
- **Permanent vs. non-permanent** canals; **alluvial vs. non-alluvial** canals (silt theories apply to alluvial canals).

Kennedy's theory (1895, Upper Bari Doab Canal)

- Silt is kept in suspension by the **eddies generated from the bed** only.
- **Critical velocity V_0** = the **non-silting, non-scouring** velocity: $V_0 = 0.55\ m\ D^{0.64}$ (m/s, D = depth in m). The original FPS form is $0.84\ D^{0.64}$ ft/s.
- **CVR** m = V/V_0. m = 1 for standard silt; 1.1–1.2 for coarser silt; 0.8–0.9 for finer silt.
- The mean velocity is found from **Kutter's** (or Manning's) formula. The design is by trial for the B/D ratio (Woods' table).
- **Drawbacks**:
  - No equation for the bed slope.
  - Silt charge and silt grade are ignored.
  - B/D is not fixed.
  - Design is by trial and error.
  - Eddies from the sides are ignored.

Lacey's regime theory (1930)

- Silt is kept in suspension by eddies generated **over the entire wetted perimeter**. The **hydraulic mean radius R** is the governing variable, not D.
- **Regime channel** = a channel in which there is no silting and no scouring.
- **Conditions for true regime**:
  - Constant discharge.
  - Constant silt charge.
  - Flow in **incoherent alluvium**, of the same grade as the silt being transported.

  True regime is rarely achieved in practice.
- **Initial regime**: only the bed slope adjusts and the section stays fixed, so Lacey's theory does not apply. **Final regime**: all variables (P, R, S) adjust, and the theory applies.
- A regime channel section is **semi-elliptical**; for design it is taken as trapezoidal with side slopes of **½H : 1V**.

KEY FORMULAE – LACEY (SI; Q IN M^3/S, D IN MM)

- Silt factor: $f = 1.76\sqrt{d_{mm}}$ (f = 1 for standard silt, d ≈ 0.32 mm).
- Velocity: $V = (Q f^2 / 140)^{1/6}$.
- Hydraulic mean radius: $R = (5/2)(V^2/f)$.
- Wetted perimeter: $P = 4.75\sqrt{Q}$.
- Area: A = Q/V.
- Bed slope: $S = f^{5/3} / (3340\ Q^{1/6})$.
- Regime flow equation: $V = 10.8\ R^{2/3} S^{1/3}$.
- Regime scour depth: $R = 0.47\ (Q/f)^{1/3}$ for a wide river; $R = 1.35\ (q^2/f)^{1/3}$ for a confined width (q per m).
- Kennedy: $V_0 = 0.55\ m\ D^{0.64}$.

Point	Kennedy	Lacey
Eddies generated from	Bed only	Whole wetted perimeter
Governing variable	Depth D	Hydraulic mean radius R
Velocity formula	Kutter's	Lacey's own (regime) equation
Silt grade	CVR m	Silt factor f

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Bed slope	No equation	Given by formula
Design	Trial and error	Direct

Canal lining & waterlogging

- **Benefits of lining**:
  - Reduces seepage loss; seepage from unlined canals is often 20–45% of the supply.
  - Prevents waterlogging.
  - Allows higher velocity and a smaller section.
  - Gives a larger command and less weed growth.
  - Lowers maintenance.
- **Types of lining**:
  - **Hard surface**: cement concrete (in-situ or precast), shotcrete, brick or tile, stone/boulder, asphaltic concrete.
  - **Earth type**: compacted earth, soil-cement.
  - **Buried membrane**: LDPE film.

  Lined canal sections are usually **triangular** for small discharges and **trapezoidal** for large ones (≈ 55 cumecs is the dividing line in Garg).
- **Waterlogging**: the root zone is saturated, so aeration is lost and salts rise to the surface (**salinity / alkalinity**, "kallar / reh / usar" lands). In India, land is treated as waterlogged when the water table is within about **2 m** of ground (2–3 m = potentially waterlogged).
- **Causes**: over-irrigation, **seepage from unlined canals**, poor natural drainage, flat topography, obstruction of natural drains (roads, railways) and heavy rainfall.
- **Control**:
  - Lining the canals.
  - Surface and **subsurface (tile) drainage**.
  - Reducing the intensity of irrigation.
  - **Conjunctive use** of surface and groundwater (pumping lowers the water table).
  - Crop rotation.
  - Bio-drainage (eucalyptus).
  - Intercepting drains.
- **Reclamation of saline/alkaline land**: leaching with excess water, **gypsum** for alkaline (sodic) soils, and salt-tolerant crops. **SAR** = $Na/\sqrt{[(Ca + Mg)/2]}$.

Canal outlets (modules)

- An **outlet** passes water from a distributary to a watercourse. For outlet discharge $q = C H^m$ and channel discharge $Q = K D^n$:
  - **Flexibility F** = (dq/q)/(dQ/Q) = **(m/n)(D/H)**.
  - **Proportional outlet**: F = 1, which requires the **setting** H/D = m/n.
  - **Hyper-proportional**: F > 1. **Sub-proportional**: F < 1.
  - **Sensitivity S** = (dq/q)/(dG/D), i.e. the rate of change of outlet discharge with change in the water level (gauge G) of the distributary.
  - **Minimum modular head** = the minimum working head needed for a semi-module to be independent of the water level in the watercourse. The **efficiency** of an outlet = head recovered ÷ head put in.

Class	Discharge depends on	Examples
Non-modular	The water levels of both the distributary **and** the watercourse	Open sluice, submerged pipe outlet
Semi-modular (flexible)	The distributary level only (independent of the watercourse)	Pipe outlet with free fall, **open flume (Crump's)**, Kennedy's gauge outlet, **AOSM** (adjustable orifice semi-module), the most common in Punjab
Modular (rigid module)	Neither: a constant discharge within limits	**Gibb's module**, Khanna's rigid module, Foote module

Canal falls

- A **fall** is needed when the ground slope is steeper than the canal bed slope, or when the canal meets a drainage. Its head is often used for **hydropower**.
- **Types**:
  - Ogee fall.
  - Rapids (long glacis, in boulder areas).
  - Stepped fall.
  - **Trapezoidal notch fall** (Reid): keeps the upstream depth constant at all discharges.
  - Vertical drop: **Sarda fall**, with a raised crest and impervious floor, developed on the Sarda canal (UP).
  - **Glacis falls**: straight glacis, Montague type (parabolic glacis), Inglis type.
  - Cylinder (well) fall: for small discharges and high drops.
- **Meter falls** (with a flume) also measure the discharge. The **straight glacis** fall uses a **hydraulic jump** for energy dissipation.

Cross-drainage (CD) works

CD work	What passes over what	Condition
Aqueduct	Canal over the drainage	Drain HFL is **below** the canal bed; the drain flows freely (open) beneath
Siphon aqueduct	Canal over the drainage	Drain HFL is **above** the canal bed; the **drain flows under pressure** (siphon) below the canal trough

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Super passage	Drainage over the canal	Canal FSL is **below** the drain bed; the canal flows freely beneath
Canal siphon (siphon)	Drainage over the canal	Canal FSL is **above** the drain bed; the **canal flows under pressure** beneath the drain
Level crossing	Both at the same level; they cross with regulators	Canal and a **large drain** at about the same level; drain has a high, short-duration flood
Inlet / outlet	Small drain admitted into the canal and let out downstream	**Small drain discharge**, at about the same level

- **Selection**: the relative levels of the canal bed/FSL and the drain bed/HFL decide the type. An **aqueduct** is preferred over a super passage because the canal stays open for inspection and the drain flow is free. **Siphon structures** need protection against silting.
- **Choice of site**: crossing at **right angles**; a straight drain reach; firm foundation.
- Aqueducts are classed by the sides of the canal trough: **Type I** earthen banks with slopes (no walls); **Type II** partly flumed (wing walls); **Type III** fully flumed (rectangular trough). Greater fluming means less masonry cost but more head loss.

Regulation works

- **Head regulator** (distributary head regulator) at the head of an off-taking channel: regulates supply into it and controls silt entry. A **meter** flume may be combined with it.
- **Cross regulator** in the parent canal, just downstream of an off-take: **heads up** the water so the off-take can draw its supply when the parent canal runs low. It is also used to close the canal downstream for repairs.
- **Canal escape** = a **safety valve** that disposes of surplus water (e.g. when a breach occurs or rain closes outlets). Types:
  - **Surface escape**: weir type or regulator type.
  - **Scouring escape**: removes silt; its crest is at the canal bed level.
- **Silt ejector (extractor)**: sits in the canal a little downstream of the head regulator and removes silt already entered. **Silt excluder**: sits in the river bed (undersluice pocket) in front of the head regulator and prevents entry (see 8.7).

MEMORY TRICK

In a CD-work name, look at **where the word "siphon" sits** to find what flows under pressure. In a **siphon aqueduct**, the drain siphons under the canal. In a **canal siphon**, the canal siphons under the drain. **Super passage** = the drain "passes super (over)" the canal.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Lacey's wetted perimeter? → **P = 4.75√Q**.
- Silt factor for d = 0.32 mm? → f = 1.76√0.32 ≈ **1.0**.
- Canal that irrigates both sides and needs no CD works? → **Watershed (ridge) canal**.
- Drain HFL above canal bed, canal carried over the drain? → **Siphon aqueduct**.
- Outlet with F = 1? → **Proportional outlet**.
- Gibb's module is an example of? → **Rigid module (modular outlet)**.

8.7 Diversion Headworks & Weirs ★★☆

- **Diversion headworks** raise the water level in the river and divert the flow into a canal. They also control the silt entering the canal.
- **Weir vs. barrage**:
  - **Weir**: the water is raised mainly by a **raised crest**, with small shutters.
  - **Barrage**: has a low crest (near river-bed level), and the ponding is done mainly by **gates**.

  A barrage gives **less afflux**, better flood control and better silt control, but costs more.
- **Afflux** = the rise in the upstream HFL caused by the structure.
- **Types of weir**: masonry/vertical-drop weir, dry stone (rock-fill) weir, concrete weir with a **sloping glacis**.

Component	Function
Weir / barrage proper	Raises the water level (ponding)
Undersluices (scouring sluices)	Keep a deep, clear channel in front of the canal head regulator and scour the deposited silt. They are at a lower crest level than the weir. Capacity is usually ≈ 2× the canal discharge or 10–20% of the design flood, whichever is more (texts vary)
Divide wall	A wall **parallel to the flow** that separates the undersluice pocket from the weir proper. It prevents cross-currents and forms a still pocket
Fish ladder	Lets fish migrate past the weir. Usually placed beside the divide wall, with baffles that reduce the velocity (≈ 3 m/s or less)
Canal head regulator	Regulates supply into the canal and limits silt entry. Usually aligned at **90°–110°** to the weir axis
Silt excluder	Tunnels in the undersluice pocket floor. The bottom (silt-laden) water is passed through the undersluices, and clear top water enters the canal
Silt ejector / extractor	In the canal, downstream of the head regulator. Ejects silt that has already entered
Guide banks (Bell's bunds)	Guide the river axially through the structure and prevent outflanking (see 8.9)

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Marginal bunds	Earthen embankments upstream that contain the afflux water

Seepage theories

- **Failure by piping (undermining)**: if the **exit gradient** exceeds the critical value, soil particles at the downstream end are washed out. The resulting **pipe** works back upstream and the structure collapses.
- **Failure by uplift**: if the floor is too thin, the uplift pressure ruptures it.
- **Critical hydraulic gradient** $i_c = (G - 1)/(1 + e) \approx$ **1**.
- **Floor thickness** against uplift: **t = h/(G − 1)**, where h = uplift head and G = specific gravity of the floor material (≈ 2.24 for concrete). Bligh uses a safety factor of **4/3**: t = (4/3) h/(G − 1).

Theory	Key idea	Formula
Bligh's creep theory (1910)	Water creeps along the contact of the floor and the soil. The loss of head is **proportional to the creep length**. Horizontal and vertical creep are **equally effective**	Safe creep length L ≥ C·H. Hydraulic gradient = H/L ≤ **1/C**
Lane's weighted creep theory (1935)	**Vertical creep is 3 times more effective** than horizontal. Slopes steeper than 45° count as vertical; flatter than 45° count as horizontal	$L_w = \Sigma V +$ **(1/3)ΣH** $\geq C_w \cdot H$
Khosla's theory (1936)	Based on **potential flow** (Laplace equation, conformal mapping). The **exit gradient** governs piping, and the outer faces of the end piles are the most effective. Uses the **method of independent variables** with corrections for interference, floor thickness and slope	$G_E =$ **(H/d)·1/(π√λ)**, with $\lambda = [1 + \sqrt{(1 + \alpha^2)}]/2$ and $\alpha =$ b/d

- **Khosla's symbols**: H = maximum seepage head, d = depth of the downstream cut-off, b = total floor length. For a floor with a downstream pile only, $G_E \to \infty$ if d ≈ 0. That is why **a downstream cut-off is essential**.
- **Khosla's pressure percentages**: φ_E, φ_D and φ_C at the key points (junction of floor and pile; bottom of pile). $\varphi_E = (1/\pi)\cos^{-1}[(\lambda - 2)/\lambda]$ and $\varphi_D = (1/\pi)\cos^{-1}[(\lambda - 1)/\lambda]$ (for a downstream pile; the residual pressures are 1 − φ for an upstream pile).
- Bligh's theory gives no separate exit-gradient check. It tends to **over-design** the floor length and does not distinguish the effect of piles.

Soil	Bligh's C (gradient 1/C)	Lane's C_w	Khosla's safe exit gradient
Light sand & mud / very fine sand, silt	18	8.5	—
Fine micaceous sand / fine sand	**15**	7.0	**1/6 – 1/7**
Coarse-grained sand	**12**	5.0	**1/5 – 1/6**
Sand mixed with gravel / boulders	9 to 4–6	3.5–2.5	**Shingle: 1/4 – 1/5**
Clay (soft → hard)	—	3.0 → 1.6	—

Note: Bligh's C values for mixed gravel/boulder soils differ slightly between Garg, Punmia and Modi. The values for fine micaceous sand (15) and coarse sand (12) are the same in all texts.

KEY FORMULAE

- Bligh: L = C·H; head lost per unit creep = H/L.
- Lane: $L_w = \Sigma V + \Sigma H/3$.
- Khosla: $G_E = (H/d)\cdot 1/(\pi\sqrt{\lambda})$; $\lambda = [1 + \sqrt{(1 + \alpha^2)}]/2$; $\alpha = b/d$.
- Uplift thickness: t = h/(G − 1). With Bligh's FOS: (4/3)h/(G − 1).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- In Lane's theory, the horizontal creep is given a weightage of? → **1/3**.
- Bligh's creep coefficient for fine micaceous sand? → **15**.
- Safe exit gradient for coarse sand (Khosla)? → **1/5 to 1/6**.
- Structure that separates the undersluice pocket from the weir proper? → **Divide wall**.
- Silt excluder is located? → **In the river bed upstream of the head regulator**. Silt ejector? → **In the canal downstream of the head regulator**.

8.8 Dams, Reservoirs & Spillways ★★☆

Gravity dams (IS 6512:1984)

Force	Magnitude / location
Weight of dam	The main **stabilising** force; acts at the centroid
Water pressure	$P = \gamma_w H^2/2$, acting at **H/3** above base. The main destabilising force
Uplift	Full reservoir head at the heel, varying linearly to the tailwater head at the toe. **Drainage galleries** reduce it (head at the drain line ≈ tailwater + ⅓ of the head difference, per USBR/IS 6512)
Silt pressure	$P_s = \frac{1}{2}\gamma' h^2 K_a$. Common equivalent-fluid values: horizontal 1360 kg/m³, vertical 1925 kg/m³
Wave pressure	Molitor wave height: $h_w = 0.032\sqrt{(VF)} + 0.763 - 0.271F^{1/4}$ for F < 32 km; $h_w = 0.032\sqrt{(VF)}$ for F > 32 km. $P_w = 2\gamma_w h_w^2$ acting at $\mathbf{3h_w/8}$ above still water
Earthquake	Inertia of the dam = $\alpha_h W$. Hydrodynamic (Zangar / von Kármán): $P_e \approx 0.555\alpha_h\gamma_w H^2$ at **4H/3π (= 0.424H)** above base
Ice pressure	≈ 250 kN/m² of ice contact. Not relevant in most of India
Wind	Usually neglected

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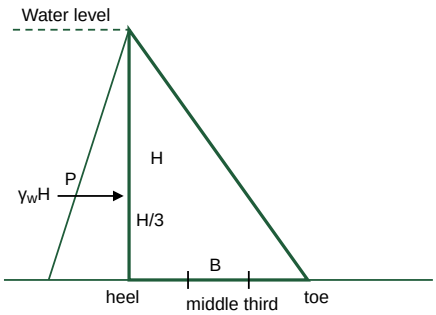

Fig 8.2 Elementary profile: a triangle with a vertical upstream face and zero top width. When the reservoir is full, the resultant must cut the base within the middle third.

KEY FORMULAE – GRAVITY DAM

- Elementary profile base width (no tension): **$B = H/\sqrt{(S_c - c)}$**. S_c = specific gravity of concrete/masonry (≈ 2.4) and c = uplift coefficient. Without uplift: $B = H/\sqrt{S_c}$.
- Base width against sliding: $B = H/[\mu(S_c - c)]$.
- Normal stress on the base: $p = (\Sigma V/B)(1 \pm 6e/B)$. **No tension** requires **$e \le B/6$** (the resultant lies in the **middle third**).
- Principal stress at the toe: $\sigma = p_v \sec^2\alpha$.
- **Limiting height** of a low gravity dam (no uplift): **$H = f/[\gamma_w(S_c + 1)]$**. With uplift: $f/[\gamma_w(S_c - c + 1)]$. For f = 3000 kN/m² and S_c = 2.4, H ≈ **88–90 m**. If H exceeds this, it is a **high gravity dam**.
- FOS against overturning = $\Sigma M_R/\Sigma M_O \ge$ **1.5** (texts give 1.5–2.0).
- Sliding factor = $\mu\Sigma V/\Sigma H \ge 1$.
- **Shear friction factor** SFF = $(\mu\Sigma V + B\,q)/\Sigma H \ge$ **3–5**.
- IS 6512 partial factors for normal loading: F_φ = **1.5**, F_c = **3.6**.

- **Modes of failure**:
  - **Overturning** about the toe.
  - **Sliding** along the base or any joint. This is the most common and critical check for low dams.
  - **Compression (crushing)** at the toe.
  - **Tension** at the heel. Masonry and concrete are weak in tension, so no tension is permitted under normal loading.
- **Reservoir empty**: the resultant lies near the **upstream (inner) middle-third** point, so the maximum stress is at the **heel**. **Reservoir full**: the resultant shifts to the **downstream middle-third** point, so the maximum stress is at the **toe**.
- **Practical profile**: has a top width (≈ 14% of H for economy, with a free-board) and a sloping upstream face near the base.
- **Galleries**: for inspection, drainage (they reduce uplift), grouting and instrumentation.

Earth dams

- **Types**:
  - **Homogeneous**: a single material, needs a drain.
  - **Zoned**: an impervious **core** with pervious shells. The most common type.
  - **Diaphragm**: a thin impervious membrane of concrete, steel or asphalt.

  By construction method: rolled-fill or hydraulic-fill.
- **Causes of failure**:
  - **Hydraulic** (≈ 40%, the largest share): **overtopping**, erosion of the upstream face by waves, toe erosion, gullying.
  - **Seepage** (≈ 30–35%): **piping** through the body or foundation, sloughing.
  - **Structural** (≈ 25–30%): slides of the slopes, foundation shear.

  Earth dams **must never be overtopped**, so an adequate spillway and free-board are vital.
- **Critical slope conditions**:
  - **Upstream slope**: **sudden drawdown**.
  - **Downstream slope**: **steady seepage** with the reservoir full.
  - **End of construction**: both slopes (pore pressure).
- **Phreatic line (seepage line)** = the top flow line, below which the soil is saturated. With a horizontal drain it is a **base parabola** (Casagrande):
  - Equation: $x = (y^2 - S^2)/2S$, with the **focus at the upstream end of the downstream filter**.
  - Focal distance $S = \sqrt{(H^2 + d^2)} - d$.
  - Entry correction: the parabola starts at **0.3 × the horizontal projection** of the wetted upstream slope.
  - Seepage discharge q = kS per unit length.
- **Filter criteria (Terzaghi)**:
  - To prevent piping: D_{15}(filter)/D_{85}(base soil) < 4–5.
  - To ensure permeability: D_{15}(filter)/D_{15}(soil) > 4–5.
- **Seepage control**:
  - Through the body: **horizontal filter blanket**, **chimney drain**, **rock toe (toe drain)**.
  - Through the foundation: cut-off trench, sheet piles, grout curtain, **upstream impervious blanket**, relief wells.
- **Top width** (empirical): H/5 + 3 m for low dams. The upstream slope is usually **flatter** than the downstream slope, because of sudden drawdown and saturation.

Dam type	Suitable site / key facts
Gravity	Strong rock foundation, any valley. Most durable, least maintenance (e.g. Bhakra)
Earth / rock-fill	Any foundation, including soil. Cheapest where materials are available; needs a separate spillway (e.g. Tehri, Hirakud)

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Arch	**Narrow V-shaped gorges** with strong abutments (width/height ratio ≈ < 5). Load goes by arch action to the abutments. **Constant-angle** arch is the most economical (central angle **133°34′**); constant-radius suits U-shaped valleys. Thin-cylinder theory: $t = \gamma_w hR/f$. Example: Idukki
Buttress	A sloping deck (Ambursen flat slab), multiple arches or massive heads, supported by buttresses. Uses less concrete; suits weak foundations; needs skilled labour

Reservoirs

- **Storage zones**:
  - **Dead storage**: below the **MDDL** (minimum drawdown level). Not drawn; receives silt.
  - **Live (useful) storage**: between the MDDL and the **FRL/NPL** (normal pool level).
  - **Surcharge (flood) storage**: between the FRL and the **MWL** (maximum water level, the HFL during the design flood). It is uncontrolled.
  - **Bank storage**: water held in the pores of the banks.
- **Mass curve (Rippl, 1883)** = accumulated inflow against time.
  - Storage needed = the maximum vertical intercept between the mass curve and demand lines drawn tangent at its high points.
  - Alternatively, from the sequent-peak algorithm.
  - A **demand line** is parallel to the slope of the demand rate.
- **Safe (firm) yield** = the maximum quantity that can be guaranteed in the driest period. **Secondary yield** = water above the safe yield in wet periods. **Design yield** = adopted with some risk (e.g. 75% dependable for irrigation, 90% for hydropower, 100% for drinking water).
- **Trap efficiency** = % of the incoming sediment retained. It is given by **Brune's curve** as a function of the **capacity/inflow (C/I) ratio**. A large C/I ratio gives a trap efficiency near 100%.
- **Reservoir sedimentation**: coarse material deposits at the head as a **delta**; fines travel as **density currents**. Design life is often taken until about 50% of the storage is lost (some texts say 80%).
- **Sedimentation control**: catchment treatment (afforestation, check dams), **sluicing / flushing** through low-level outlets, **venting density currents**, and providing adequate dead storage.
- **Empirical area-reduction** and area-increment methods (Borland–Miller) distribute sediment within the reservoir.

Spillways, energy dissipators & gates

Spillway	When / key fact
Ogee (overflow)	Most common, on gravity dams. The crest follows the **lower nappe of a sharp-crested weir**. WES profile: $x^{1.85} = 2H_d^{0.85}y$. $Q = C\,L\,H_e^{3/2}$ ($C \approx 2.2$ in SI)
Chute (trough)	Steep open channel; for **earth/rock-fill dams**, placed on a flank or in a saddle
Side-channel	**Narrow valleys** with no room for a long crest. Flow turns about **90°** into a channel parallel to the crest
Shaft (morning-glory / bell-mouth)	A circular crest drops into a vertical shaft and then a tunnel. For narrow gorges, small discharges and earth dams with diversion tunnels. Becomes **submerged (no extra capacity) at high heads**
Siphon	**Automatic**. Discharges large flows at a **nearly constant reservoir level** after priming; limited capacity. Risks: clogging, vibration
Free overfall (straight drop)	Thin arch dams and weirs with a small drop
Emergency (fuse-plug / breaching section)	Auxiliary. Operates only in an extreme flood above the design flood

Tail water (TWRC) vs. jump height (JHC) curve	Energy dissipator
TWRC = JHC at all discharges (ideal)	**Horizontal apron** with a hydraulic-jump stilling basin
TWRC above JHC at all discharges (excess tailwater)	**Roller bucket** (submerged bucket), or a sloping apron above the bed
TWRC below JHC at all discharges (deficient tailwater)	**Ski-jump / flip bucket** (needs good rock downstream), or a sunken / sloping apron below bed
TWRC above JHC at low Q, below at high Q (or vice versa)	Sloping apron, partly above and partly below the bed

- **Hydraulic jump by Froude number** F_1:
  - 1–1.7: undular.
  - 1.7–2.5: weak.
  - 2.5–4.5: oscillating (worst, sends waves downstream).
  - **4.5–9: steady** (the best jump).
  - > 9: strong.

  USBR basins: Type IV for F 2.5–4.5. Type III for F > 4.5 with V < about 18 m/s (chute blocks, baffle blocks, end sill). Type II for F > 4.5 with high velocity (no baffle blocks). Indian code: **IS 4997**.
- **Gates**:
  - **Radial (Tainter) gate**: the most common spillway gate. The water thrust passes through the **trunnion pin**, so the **hoisting effort is small**.
  - **Vertical lift gates**: fixed-wheel or slide.
  - **Drum gate**, **rolling gate**, **flap gate**.
  - **Stop logs**: for maintenance closure.

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MEMORY TRICK

Tailwater "**Too High → Roll; Too Low → Ski**". Too much tailwater calls for a **roller** bucket; too little calls for a **ski-jump**. For dam safety, "**Earth: never overtop; Gravity: never tension.**"

PREVIOUSLY ASKED / LIKELY QUESTIONS

- For no tension in a gravity dam, the resultant must lie within? → **Middle third of the base**.
- Base width of the elementary profile with no uplift (S_c = 2.4)? → B = H/√2.4 ≈ **0.65 H**.
- Critical condition for the upstream slope of an earth dam? → **Sudden drawdown**.
- Shape of the phreatic line in an earth dam? → **Parabola**.
- Trap efficiency of a reservoir is read from? → **Brune's curve** (C/I ratio).
- Spillway for a narrow valley where the crest cannot be long? → **Side-channel spillway**.

8.9 River Engineering & Water Resources ★☆☆

- **River training objectives**:
  - **High-water training**: flood control, using **levees/embankments**.
  - **Low-water training**: depth for navigation.
  - **Mean-water training**: for sediment and to keep the channel in shape.
- **Guide banks (Bell's bunds)**:
  - Used at barrages and bridges on alluvial rivers. They confine the river to **Lacey's waterway** (P = 4.75√Q) and stop it from outflanking.
  - Length: upstream ≈ **1.0–1.5 L** and downstream ≈ **0.1–0.2 L** (L = width between abutments).
  - Ends: curved heads, with a **launching apron** and **stone pitching**.
- **Groynes (spurs)**: projected from the bank into the river.
  - **Repelling groyne** points **upstream** and pushes the flow away from the bank.
  - **Attracting groyne** points **downstream** and draws the flow towards the bank.
  - **Deflecting groyne** is short, at right angles to the bank.

  Groynes can be permeable or impermeable. A **T-headed** groyne is called a **Denehy groyne**.
- **Other works**:
  - Marginal embankments (levees).
  - Bank revetment / pitching.
  - Pitched islands.
  - **Artificial cut-offs** (to straighten a meander loop).
  - Closing dykes.
  - Sills.
- **Meandering**: alluvial rivers develop a serpentine course. Erosion occurs at the **concave (outer) bank** and deposition at the **convex (inner) bank**.
  - **Tortuosity / sinuosity** = curved length ÷ straight (valley) length. A river is called meandering if this is about > 1.5.
  - Meander length and meander belt vary about as **√Q** (Inglis, Lacey).
  - A cut-off of a loop leaves an **ox-bow lake**.
- **River stages**: **rocky/incised** (hilly), **boulder**, **alluvial** (aggrading, degrading, meandering) and **tidal/deltaic**.

Institution	Key facts
CWC – Central Water Commission	The premier technical body for **surface water**. HQ **New Delhi**, under the **Ministry of Jal Shakti** (Dept. of Water Resources, RD & GR). Set up in **1945** as CWINC. Handles **flood forecasting**, hydrological observation, dam-safety support and appraisal of projects. Not to be confused with the Central Warehousing Corporation
CGWB – Central Ground Water Board	Groundwater survey, monitoring and assessment. HQ **Faridabad**. The **CGWA** regulates groundwater extraction
NWDA – National Water Development Agency (1982)	Studies and DPRs for **interlinking of rivers**
CWPRS, Pune (1916)	Hydraulic model studies
NIH, Roorkee (1978)	National Institute of Hydrology
NDSA	National Dam Safety Authority, under the **Dam Safety Act, 2021**

- **National Water Policy**: issued in **1987, 2002 and 2012**. The 2012 policy is the version exams use.
  - It treats water as an **economic good** after a minimum for basic needs.
  - Priority goes to **drinking water** first, with ecological needs also emphasised.
  - It promotes the river basin/sub-basin as the unit of planning, water-use efficiency, a **National Framework Law**, setting up Water Regulatory Authorities, and adaptation to climate change.

  A draft for a new policy was prepared later (Mihir Shah committee, 2019–20).
- **India's water resources**:
  - Annual precipitation ≈ **4000 BCM**.
  - Average annual water availability ≈ **1999 BCM** (CWC reassessment, 2019).
  - Utilisable ≈ **1122 BCM** (≈ 690 surface + 432 ground).
  - India has about **18%** of the world's population but about **4%** of its fresh water.

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- **Interlinking of Rivers (NPP 1980)**: **30 links**, 16 in the Peninsular component and 14 in the Himalayan component. The **Ken–Betwa link** (MP–UP) is the first to be taken up for implementation.
- India has **over 6,000 large dams** (National Register of Large Dams). India ranks third in the world after China and the USA.

Dam / work	River, State	Fact
Tehri	Bhagirathi, Uttarakhand	**Highest dam in India** (≈ 260 m); earth & rock-fill
Bhakra	Sutlej, Himachal Pradesh	Among the highest **concrete gravity** dams (≈ 226 m); reservoir **Gobind Sagar**
Hirakud	Mahanadi, Odisha	**Longest dam in India** (main dam ≈ 4.8 km; ≈ 25.8 km with dykes)
Sardar Sarovar	Narmada, Gujarat	Large **concrete gravity** dam (≈ 163 m). Narmada Main Canal is the longest lined irrigation canal
Indira Sagar	Narmada, Madhya Pradesh	Among the largest reservoirs in India by storage
Nagarjuna Sagar	Krishna, Telangana/AP	One of the largest **masonry** dams in the world
Idukki	Periyar, Kerala	Double-curvature **arch dam**
Kallanai (Grand Anicut)	Kaveri, Tamil Nadu	**Oldest** functioning water-diversion structure (≈ 2nd century AD, Karikala Chola)
Farakka Barrage	Ganga, West Bengal	Diverts water to the **Hooghly** to keep Kolkata port navigable
Koyna	Koyna, Maharashtra	Associated with the 1967 earthquake (**reservoir-induced seismicity**)
Indira Gandhi Canal	From Harike barrage (Sutlej–Beas), Rajasthan	**Longest canal** in India

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Highest dam in India? → **Tehri**. Longest dam? → **Hirakud**.
- Groyne pointing upstream that pushes flow away from the bank? → **Repelling groyne**.
- Guide banks for barrages on alluvial rivers are known as? → **Bell's bunds**.
- Headquarters of the Central Ground Water Board? → **Faridabad**.
- First river-link project taken up under ILR? → **Ken–Betwa link**.

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9. Environmental Engineering

> **NOTE**
>
> Environmental Engineering usually gives **6–9 MCQs** in civil AE/JE papers. Most are number-recall questions: per-capita demand, IS 10500 limits, filter rates, self-cleansing velocity, BOD constants, ASP parameters, NAAQS/AQI values, noise standards and the colour codes for biomedical waste. Learn the tables in this chapter thoroughly. Questions on formulae (fire demand, population forecasting, BOD kinetics, decibel addition) are one-step numericals.

9.1 Water Demand & Population Forecasting ★★★

- **Types of demand**: domestic (≈ **50–60%** of total), commercial & industrial (≈ 20–25%), public/civic use (≤ **5%**), fire demand, and **losses & wastes** (leakage, unauthorised connections, meter slip).
- **Per-capita demand** (lpcd) = total annual quantity ÷ (population × 365). It is an **annual average** daily figure.
- Domestic breakdown for the classical **135 lpcd** (IS 1172): drinking 5, cooking 5, bathing **55** (largest), washing clothes 20, utensils 10, house washing 10, WC flushing 30.
- **Unaccounted-for water (UFW / NRW)**: CPHEEO limits it to **15%**. The per-capita norms below exclude UFW, so it is added on top.
- Factors affecting per-capita demand: climate, size of city (bigger city → higher demand), living standard, industries, **cost of water** (higher cost → lower use), quality, **pressure** (higher pressure → more use and waste), system of supply (intermittent supply reduces use but contaminates), metering (reduces use).

Situation (CPHEEO Manual on Water Supply & Treatment)	Recommended supply (lpcd)
Towns with piped supply but **no sewerage**	**70**
Cities with piped supply where **sewerage exists / is planned**	**135**
Metropolitan / mega cities (population > 10 lakh) with sewerage	**150**
Supply through **public stand-posts**	**40**
Rural (Jal Jeevan Mission, FHTC norm since 2019)	**55**
IS 1172:1993: population > 1 lakh with full flushing	150–200 (may be reduced to 135 for LIG/EWS)

Building (IS 1172 / NBC 2016)	Water demand
Hospital > 100 beds / ≤ 100 beds	**450** / **340** L per bed per day
Hotels	180 L per bed
Offices; day schools	**45** L per head
Boarding schools; nurses' homes	135 L per head
Factories with / without bathrooms	45 / 30 L per head
Restaurants; cinemas	70 L per seat; 15 L per seat

KEY FORMULAE – FIRE DEMAND (P = POPULATION IN THOUSANDS)

- **Kuichling**: Q = **3182 √P** L/min
- **Freeman**: Q = **1136 (P/5 + 10)** L/min
- **Buston**: Q = **5663 √P** L/min (gives the highest value)
- **National Board of Fire Underwriters (NBFU)**: Q = **4637 √P (1 − 0.01 √P)** L/min (for central congested high-value areas)
- **CPHEEO**: fire demand = **100 √P kL/day** (for communities with population > 50,000)
- Goodrich formula (variation): $p = 180\ t^{-0.10}$, where p = % of annual average demand and t = period in days (t = 1 day gives 180%)

- **Variations in demand**: seasonal (summer peak), daily, hourly (morning peak ≈ 6–9 am).
- **Maximum daily demand** = **1.8 ×** average daily demand.
- **Maximum hourly demand** = 1.5 × average hourly demand of the maximum day = **2.7 ×** annual average hourly demand.
- **Coincident draft** = maximum daily demand + fire demand. Distribution mains are designed for the **greater of** (maximum hourly demand) and (coincident draft).
- **Design basis of components**: source and intake → maximum daily demand. Pipes from intake to WTP and the WTP itself → maximum daily demand (WTP runs 24 h). Pumps → maximum daily demand + standby. Distribution system → **maximum hourly demand** (or coincident draft).
- **CPHEEO peak factors for distribution** (on average flow): population up to 50,000 → **3.0**; 50,000–2 lakh → **2.5**; above 2 lakh → **2.0**; rural schemes → 3.0.

Component (CPHEEO)	Design period (years)
Storage by **dams**	**50**
Infiltration works; pump-house (civil works)	30
Raw & clear water conveying mains; distribution system	**30**
Water treatment units; **electric motors & pumps**	**15**
Clear water reservoirs, balancing tanks, service reservoirs	15
Pipe connections to treatment units, small appurtenances	30
Overall water supply scheme (normal practice)	**30** (base year = year of commissioning)

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KEY FORMULAE – POPULATION FORECASTING

- **Arithmetic increase**: $P_n = P_0 + n\,\bar{x}$ ($\bar{x}$ = average increase per decade; dP/dt = constant)
- **Geometric increase**: $P_n = P_0(1 + r)^n$; r = geometric mean of the decadal growth rates = $(r_1\, r_2 \ldots r_t)^{1/t}$
- **Incremental increase**: $P_n = P_0 + n\,\bar{x} + \mathbf{n(n + 1)/2 \cdot \bar{y}}$ ($\bar{y}$ = average incremental increase)
- **Logistic (Verhulst, S-curve)**: $P = P_s / (1 + m\, e^{nt})$; saturation population $P_s = [2P_0P_1P_2 - P_1^2(P_0 + P_2)] / (P_0P_2 - P_1^2)$, using three populations at equal time intervals

Method	Assumption	Suitable for / result
Arithmetic increase	Constant increase per decade	**Old, large, saturated** cities. Gives the **lowest** estimate
Geometric increase	Constant percentage growth	**Young, rapidly growing** cities. Gives the **highest** estimate
Incremental increase	The increase itself grows by a constant amount	Average cities; result lies between arithmetic and geometric
Decreasing rate of growth	Growth rate falls as the city approaches saturation	Cities nearing saturation
Logistic curve	S-shaped growth up to a saturation value	Long-range forecasts. Growth is fastest at the point of inflection ($P = P_s/2$)
Graphical comparison	Growth follows that of similar, larger cities	Cities with similar character
Simple graphical / ratio / zoning (master plan)	Extrapolation; city/nation ratio; planned density	Planned towns (zoning method)

- **Sources of water**: **surface** (rivers, lakes, impounding reservoirs, streams) and **sub-surface** (springs, open and tube wells, **infiltration galleries**, infiltration wells, Jack wells). Rainwater harvesting is a supplementary source.
- Infiltration gallery = horizontal perforated conduit laid across or along a river bed to collect sub-surface flow. The water it collects is naturally filtered.
- **Intakes**: river intake, reservoir intake, lake intake, canal intake. A **twin-tower intake** (intake well plus jack well) is used on rivers. Intakes are located **upstream** of the town's sewage outfall and draw from several levels so that the best-quality water can be taken. Intake velocity is kept low so that fish and floating matter are not drawn in.

MEMORY TRICK

"**Kuichling 3-1-8-2, Buston 5-6-6-3**" (both × √P). Peak factors: "**1.8 day, 2.7 hour**" (2.7 = 1.8 × 1.5). For population methods remember "**A**rithmetic for **A**ged cities, **G**eometric for **G**rowing cities".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Per-capita supply recommended by CPHEEO for a city with sewerage? → **135 lpcd**.
- Maximum hourly demand as a multiple of the average? → **2.7**.
- Population method that gives the highest forecast? → **Geometric increase**.
- CPHEEO fire demand formula? → **100√P kL/day**, P in thousands.
- Design period of a WTP / of the distribution system? → **15 yr / 30 yr**.

9.2 Water Quality & Standards ★★★

- **Physical parameters**: temperature, **turbidity** (NTU, measured by a **nephelometer**; older instruments are the Jackson candle and Baylis turbidimeter; 1 JTU ≈ 1 mg/L SiO_2), **colour** (Hazen / platinum-cobalt units, read on a tintometer), taste & odour (threshold odour number, TON), electrical conductivity (TDS ≈ 0.55–0.7 × EC in µS/cm).
- **Chemical parameters**: pH, TDS, hardness, alkalinity, chlorides, sulphates, fluoride, nitrogen forms, iron, manganese, toxic metals, DO.
- **Nitrogen forms show the age of pollution**: **free ammonia** → recent pollution; **nitrites** → partly oxidised organic matter (most dangerous stage); **nitrates** → old, fully oxidised pollution.
- **Biological parameters**: bacteria (coliforms), viruses, protozoa, algae (taste and odour problems; controlled with **copper sulphate**).

Parameter (IS 10500:2012)	Acceptable limit	Permissible (no alternative source)
pH	**6.5–8.5**	No relaxation
Turbidity (NTU)	**1**	**5**
Colour (Hazen units)	5	15
Total dissolved solids (mg/L)	**500**	**2000**
Total hardness as $CaCO_3$	**200**	**600**
Total alkalinity as $CaCO_3$	200	600
Calcium / Magnesium	75 / 30	200 / 100
Chloride	**250**	**1000**
Sulphate	200	400
Fluoride	**1.0**	**1.5**
Nitrate (as NO_3)	**45**	No relaxation
Iron	**0.3**	No relaxation (was 1.0 in IS 10500:1991)
Manganese	0.1	0.3
Copper / Zinc	0.05 / 5	1.5 / 15

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Aluminium	0.03	0.2
Arsenic	**0.01**	No relaxation (after the 2015 amendment)
Lead / Cadmium / Mercury	0.01 / 0.003 / 0.001	No relaxation
Total chromium / Cyanide	0.05 / 0.05	No relaxation
Residual free chlorine	**0.2 (minimum)**	1.0
Phenolic compounds (as C_6H_5OH)	0.001	0.002
Total coliform / E. coli	**Shall not be detectable in any 100 mL sample**	

- All values are in mg/L unless stated otherwise.

CODE UPDATE

IS 10500:2012 (2nd revision) replaced IS 10500:1991. It renamed the limits "desirable/permissible" as **"acceptable/permissible"**, tightened iron to 0.3 mg/L with no relaxation, and added new parameters (e.g. Ba, Mo, Ag, chloramines, PAHs, pesticides). Arsenic's 0.05 relaxation was later withdrawn. For bottled water, see IS 14543 (packaged drinking water) and IS 13428 (natural mineral water).

- **Hardness** is caused by multivalent cations (Ca^{2+}, Mg^{2+}; also Fe^{2+}, Mn^{2+}, Sr^{2+}). It is expressed in **mg/L as $CaCO_3$**.
- **Temporary (carbonate) hardness** comes from bicarbonates of Ca and Mg. It is removed by **boiling** or by adding lime.
- **Permanent (non-carbonate) hardness** comes from sulphates, chlorides and nitrates of Ca and Mg. It is removed by **soda ash (lime-soda process)** or by zeolite.
- Hardness = Ca^{2+}(mg/L) × 50/20 + Mg^{2+}(mg/L) × 50/12. Also, 1 meq/L = 50 mg/L as $CaCO_3$.
- If alkalinity ≥ total hardness → carbonate hardness = total hardness. If alkalinity < total hardness → carbonate hardness = alkalinity.
- Hardness is measured by **EDTA titration** with Eriochrome Black T indicator (wine red → blue).
- Classification (mg/L as $CaCO_3$): soft 0–75, moderately hard 75–150, hard 150–300, very hard > 300.
- **Alkalinity** = capacity to neutralise acid, due to OH^-, CO_3^{2-} and HCO_3^-. **Phenolphthalein (P) alkalinity** is titrated to pH 8.3; **total (methyl orange, M) alkalinity** to pH ≈ 4.5. OH^- and HCO_3^- cannot coexist.
- **Chlorides** are measured by Mohr's method ($AgNO_3$ titration with K_2CrO_4 indicator). **Fluoride** is measured by the SPADNS method or an ion-selective electrode.

Hardness unit	Equivalent (mg/L as $CaCO_3$)
1 degree Clark (English) = 1 grain per imperial gallon	**14.3**
1 French degree	10
1 German degree	17.8
1 ppm	1

- **Indicator organism**: **E. coli** (coliform group). It is harmless itself, but its presence shows faecal contamination. It is chosen because it is abundant in faeces, survives longer than pathogens and is easy to detect.
- **Multiple tube fermentation** gives the **MPN (most probable number) per 100 mL**. It has three tests: **presumptive** (lactose broth, gas within 48 h at 35–37 °C), **confirmed** (BGLB broth) and **completed**. **Membrane filter technique**: 0.45 µm filter, colonies counted directly (results in 24 h).
- **Faecal (thermotolerant) coliforms** are incubated at **44.5 °C**. The ratio FC/FS (faecal streptococci) is > 4 for human pollution and < 0.7 for animal pollution.

Disease / condition	Cause
Cholera	Bacterium *Vibrio cholerae*
Typhoid; bacillary dysentery	*Salmonella typhi*; *Shigella*
Amoebic dysentery; giardiasis	Protozoa *Entamoeba histolytica*; *Giardia*
Infectious hepatitis (jaundice), polio	Virus (Hepatitis A / E, polio virus)
Guinea worm (dracunculiasis)	Cyclops-borne; India declared free in 2000
Fluorosis (dental mottling → skeletal)	Fluoride > 1.5 mg/L. Fluoride < 0.6–1.0 mg/L causes **dental caries**
Blue baby syndrome (methaemoglobinaemia)	**Nitrate** > 45 mg/L
Minamata disease (Japan, 1950s)	**Mercury** (methyl mercury in fish)
Itai-itai ("ouch-ouch") disease	**Cadmium**
Black-foot disease, arsenicosis	**Arsenic** (West Bengal, Bangladesh)
Plumbism; goitre	Lead; iodine deficiency
Laxative effect	Sulphate ($MgSO_4$) > 400–500 mg/L

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Permissible fluoride in drinking water (IS 10500:2012)? → **1.5 mg/L** (acceptable 1.0).
- Acceptable TDS / hardness limits? → **500 / 200 mg/L**.
- Methaemoglobinaemia is caused by excess of? → **Nitrates**.
- Itai-itai disease is caused by? → **Cadmium**.
- Presence of nitrites in water indicates? → **Partly oxidised (active) organic pollution**.
- 1 degree Clark equals? → **14.3 mg/L as $CaCO_3$**.

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9.3 Water Treatment ★★★

- **Conventional sequence** (surface water): intake/screening → (aeration) → **coagulation (flash mixing)** → **flocculation** → **sedimentation (clarifier)** → **rapid sand filtration** → **disinfection** → clear-water reservoir → distribution. Groundwater often needs only disinfection, or aeration followed by filtration for iron.
- **Screens**: coarse screens (bars 20–50 mm apart) followed by fine screens. They protect pumps from floating matter.
- **Plain sedimentation** (no chemicals) removes about 60–70% of suspended solids. It works by gravity settling of **discrete particles (Type I)**. Flocculent settling is Type II. Hindered/zone settling is Type III. Compression settling is Type IV (sludge thickeners).
- **Hazen's theory**: in an ideal settling tank, removal efficiency depends on the **surface overflow rate (SOR)**, i.e. on surface area, and is **independent of depth**. Particles with $v_s \geq$ SOR are removed 100%; smaller ones are removed in the fraction v_s/SOR.
- Rectangular tanks: L : B ≈ 3:1 to 5:1, depth 2.5–5 m (typically 3–4.5 m). Circular clarifiers: diameter up to about 60 m, with a sludge scraper. Floor slope is about 1 in 12 (circular) and 1 in 100 (rectangular).
- **Tube settlers / plate settlers** increase the effective surface area. The tubes are inclined at about 60°.

KEY FORMULAE – SEDIMENTATION

- **Stokes' law** (laminar, Re < 0.5, d < 0.1 mm): $v_s = g\,(G_s - 1)\,d^2 / (18\,\nu) = g\,(\rho_s - \rho_w)\,d^2 / (18\,\mu)$
- Surface overflow rate (SOR) = Q / (B L) ($m^3/m^2/day$; same units as velocity)
- Detention time t_d = V/Q. Weir loading = Q / weir length

Unit	Typical detention time	Typical SOR ($m^3/m^2/d$)
Flash (rapid) mixer	**30–60 s**	–
Flocculator	**10–40 min** (≈ 30 min)	–
Plain sedimentation tank	**4–8 h**	12–18
Sedimentation with coagulation (clariflocculator)	**2–4 h** (≈ 2–2.5 h)	24–40
Grit chamber (sewage)	**30–60 s**	–
Primary clarifier (sewage)	**1.5–2.5 h** (≈ 2 h)	30–40 (avg flow)
Secondary clarifier after ASP / trickling filter	1.5–2.5 h	15–35
Septic tank	**24 h** (12–72)	–

- **Coagulation** destabilises colloids (zeta potential reduction, charge neutralisation, sweep floc). **Flocculation** is slow mixing that builds flocs.
- **Alum** = $Al_2(SO_4)_3 \cdot 18H_2O$. It is the most common coagulant. Effective pH is **6.5–8.5**, and the usual dose is **5–30 mg/L** (up to 85 mg/L for turbid monsoon water). It needs natural alkalinity: $Al_2(SO_4)_3 + 3Ca(HCO_3)_2 \rightarrow 2Al(OH)_3\downarrow + 3CaSO_4 + 6CO_2$. 1 mg/L alum consumes ≈ 0.45–0.5 mg/L alkalinity (as $CaCO_3$). Alum is cheap, but its floc is light and it adds permanent hardness and CO_2.
- **Optimum coagulant dose** is found by the **jar test**.
- Other coagulants: **ferrous sulphate (copperas)** works at pH > 8.5 and is usually used with lime. Chlorinated copperas ($FeSO_4 + Cl_2$ → ferric sulphate + ferric chloride) works over pH 3.5–6.5 and above 8.5, and also removes colour. **Ferric chloride** works at pH 3.5–6.5 and > 8.5. **Sodium aluminate** works at pH 6–8.5, adds alkalinity and also removes hardness. Polyaluminium chloride (PAC) and polyelectrolytes are coagulant aids. Bentonite clay adds weight to the floc.

KEY FORMULAE – MIXING

- Velocity gradient (Camp & Stein): $\mathbf{G = \sqrt{P / \mu V}}$ (s^{-1}); P = power input (W), V = volume (m^3), μ = dynamic viscosity ($N{\cdot}s/m^2$)
- Rapid mix: **G ≈ 300–1000 s^{-1}** (CPHEEO ≥ 300), t = 30–60 s
- Flocculation: **G ≈ 20–75 s^{-1}**, **Gt ≈ 10^4–10^5** (dimensionless), t = 10–40 min. Paddle tip speed 0.2–0.6 m/s

Feature	Slow sand filter (SSF)	Rapid sand (gravity) filter (RSF)	Pressure filter
Filtration rate	**100–200 L/h/m²** (2.4–4.8 $m^3/m^2/d$)	**3000–6000 L/h/m²** (≈ 30 × SSF; CPHEEO 4.8–6 m/h)	**6000–15,000 L/h/m²**
Effective size of sand (D_{10})	**0.2–0.35 mm**	**0.35–0.6 mm** (CPHEEO 0.45–0.7)	Similar to RSF
Uniformity coefficient (D_{60}/D_{10})	**2–3** (up to 5)	**1.3–1.7**	1.3–1.7
Sand depth	≈ 90–110 cm	60–75 cm	Inside a closed steel shell
Pre-treatment	Plain sedimentation only (raw turbidity < ≈ 30–50 NTU)	**Coagulation + sedimentation essential**	Coagulant dosed in line
Cleaning	**Scraping** top 1.5–3 cm of sand every 1–3 months	**Back-washing** every 24–48 h with 2–5% of the filtered water	Back-washing
Mechanism	Biological (**Schmutzdecke** / dirty skin) + straining	Mechanical straining, sedimentation, flocculation in pores	Same as RSF

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Bacterial removal	**98–99.5%** (very high)	**80–90%** (post-chlorination needed)	Lower than RSF
Area / cost	Large area, low running cost, suits villages	Small area (≈ 1/20–1/30 of SSF), skilled operation	Compact. Used for industries, swimming pools, small colonies
Terminal head loss	≈ 0.7–1.2 m	≈ **2–3 m** (CPHEEO 2.5 m)	Up to 3–6 m

- **Back-washing** of an RSF: the bed expands by about 20–50%, and wash water rises at about 0.3–0.9 m/min (often with air scour first). Wash water troughs collect the dirty water.
- **Filter troubles**:
  - **Mud balls**: mud + sand + coagulant. Caused by inadequate back-washing. Remedy: surface wash or caustic soda treatment.
  - **Cracking and shrinkage** of the bed.
  - **Air binding**: when the **loss of head exceeds the static head** above the sand, negative pressure develops, dissolved air is released and the bed is blocked. Remedy: do not run beyond the design head loss, and wash frequently.
  - **Sand incrustation** ($CaCO_3$ deposits) and **jetting / sand boils**.
- **Negative head** develops when the head loss exceeds the depth of water above the sand.
- **Dual-media filter**: anthracite over sand (coarse to fine in the direction of flow). It gives higher rates and longer runs.
- **Disinfection** kills pathogens; it is not sterilisation. The most common disinfectant is **chlorine**, which is cheap, reliable and leaves a **residual**.
- $Cl_2 + H_2O \rightarrow$ **HOCl** + HCl, and $HOCl \rightleftharpoons H^+ + OCl^-$. **HOCl is ≈ 80–100 times more effective** than OCl^-. HOCl dominates at **low pH (< 7)**, the two are about 50 : 50 at pH ≈ 7.5, and OCl^- dominates above pH ≈ 8.5–9. Chlorination is therefore **more effective at lower pH**.
- **Free available chlorine** = HOCl + OCl^-. **Combined chlorine** = **chloramines** (NH_2Cl monochloramine, $NHCl_2$ dichloramine, NCl_3 trichloramine). Chloramines are weaker and slower, but stable and long-lasting in the distribution system, and they form fewer THMs.
- **Chlorine demand** = chlorine applied − chlorine residual.
- **Break-point chlorination**: the dose beyond which any further chlorine appears as **free residual**. The curve shows (i) an initial demand from reducing agents (Fe^{2+}, H_2S), (ii) a rise as chloramines form, (iii) a fall as chloramines are destroyed (break point; $Cl_2 : NH_3\text{-}N \approx 7.6 : 1$), and (iv) a linear rise of free residual. Tastes and odours also disappear beyond the break point.
- **Residual**: free chlorine of **0.2 mg/L at the consumer's tap**, after a **contact time of 30 min** (CPHEEO). Raise it to 0.5–1 mg/L during epidemics or to protect against viruses.
- **Super-chlorination**: a dose far beyond the break point (residual 1–2 mg/L), used in emergencies. It is followed by **dechlorination** with sodium thiosulphate, sodium bisulphite, SO_2 or activated carbon.
- **Plain chlorination** = chlorination of raw water with no other treatment. **Pre-chlorination** = before filtration (controls algae). **Post-chlorination** = after filtration (the normal practice). **Double chlorination** = both.
- **Bleaching powder** ($CaOCl_2$) has about **33–35% available chlorine** when fresh and deteriorates on storage. Chlorine gas is liquefied in cylinders and dosed by a chlorinator. Chlorine leaks are detected with **ammonia** (white fumes).
- Chlorination of humic matter forms **trihalomethanes (THMs)**, which are carcinogenic. Remedy: remove the precursors first, or use ozone/chloramines.
- **Ozone (O_3)**: the strongest common oxidant, and better against viruses and cysts. It removes colour, taste and odour, but leaves **no residual** and is costly.
- **UV (≈ 254 nm**, low-pressure mercury lamp): no residual and no by-products, but needs clear water. Other methods: boiling, silver (Katadyn process), potassium permanganate (for wells), iodine and bromine (swimming pools/troops), excess lime.
- **Chick's law**: $N_t = N_0\, e^{-kt}$ (first-order kill).
- **Aeration** removes CO_2, H_2S (rotten-egg odour) and volatile tastes/odours, adds DO, and oxidises Fe^{2+} and Mn^{2+}. Types: **cascade**, multiple tray (coke trays), spray nozzles, diffused air.
- **Iron & manganese removal**: aeration → sedimentation → filtration. Fe^{2+} oxidises easily at pH ≈ 7–8. Mn^{2+} needs pH > 9 or a strong oxidant such as $KMnO_4$ or chlorine (manganese zeolite). Iron gives a red-brown stain and Mn a black stain on clothes and fixtures, and both encourage iron bacteria (Crenothrix).
- **Softening**:
  - **Lime-soda process**: lime $Ca(OH)_2$ removes carbonate hardness and Mg. **Soda ash Na_2CO_3** removes non-carbonate (permanent) hardness. It also removes Fe, Mn and some bacteria, and lowers TDS. Drawbacks: large sludge volumes and the need for **recarbonation** (CO_2) to prevent incrustation. Residual hardness is about 30–50 mg/L. Excess-lime treatment is used for Mg.
  - **Ion exchange / zeolite (base exchange) process**: $Na_2Z + Ca^{2+} \rightarrow CaZ + 2Na^+$. It gives **zero hardness**. The bed is regenerated with **NaCl brine (5–10%)**. It is unsuitable for turbid water or water with Fe/Mn, and it does **not reduce TDS** (sodium increases). Demineralisation uses cation (H^+) and anion (OH^-) resins.

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- **Defluoridation**: the **Nalgonda technique** (developed by **NEERI, Nagpur**, 1974–75) adds **alum + lime + bleaching powder**, followed by flocculation, sedimentation and filtration. It suits fill-and-draw household and community units. Other methods: **activated alumina** (regenerated with NaOH), bone char, RO. **Fluoridation** (adding fluoride where it is < 0.6 mg/L) uses NaF or sodium silicofluoride.
- **Desalination**: **reverse osmosis (RO)** applies pressure greater than the osmotic pressure across a semi-permeable membrane. Brackish water needs about 10–25 bar and sea water (TDS ≈ 35,000 mg/L) about 55–80 bar. Other methods: multi-stage flash distillation, electrodialysis, solar stills. Examples in India: the Minjur and Nemmeli plants (Chennai).
- **Taste & odour**: activated carbon (powdered or granular), aeration, $KMnO_4$, ozone. Algae are controlled with **copper sulphate**.

MEMORY TRICK

"**Slow = Scrape, Rapid = Reverse wash**". SSF is **30 times slower** but **removes bacteria better** (98–99% vs 80–90%). For chlorine: "**H**OCl is the **H**ero at **H**igh acidity (low pH)".

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Efficiency of an ideal settling tank depends on? → **Surface overflow rate (surface area)**, not depth.
- Rate of filtration of a slow sand filter? → **100–200 L/h/m²**.
- Air binding in a rapid sand filter is caused by? → **Head loss exceeding the static head (negative pressure)**.
- Most effective form of free chlorine? → **HOCl** (at low pH).
- Nalgonda technique is used for? → **Defluoridation** (alum + lime + bleaching powder).
- Zeolite softening reduces hardness to? → **Zero**.

9.4 Water Distribution ★★☆

- **Methods of distribution**: **gravity system** (source at high level; most reliable and economical), **pumping without storage** (direct pumping), and **combined system** (pumping to an elevated reservoir then gravity, the **most common**; pumps run at a uniform rate).
- **Continuous supply** (24 × 7): the ideal. It keeps pipes full and positive-pressure, so contamination is unlikely. **Intermittent supply**: supply only for certain hours. Pipes empty and develop negative pressure, so polluted water is sucked in (**back-siphonage**). People store water and waste it.

Layout	Advantages	Disadvantages / used for
Dead-end / tree system	Simple, cheap, easy design; fewer valves	**Stagnant water at dead ends**; large area affected during repairs; poor fire supply. Used in **old towns with irregular growth**
Grid-iron (reticulation / interlaced)	Water circulates freely, **no dead ends**, little area affected during repairs, good fire flow from several directions	More pipes and valves, costly, design complex (**Hardy Cross**). Used in **well-planned towns with a rectangular street layout**
Ring / circular	Every locality is fed from two sides; good for fire fighting	Many valves and long pipes. Used in towns with well-planned roads (circular localities)
Radial	Water is distributed radially from a zonal reservoir: quick service, high pressure, less head loss	Needs zonal reservoirs. Used in towns with **radial roads**

- **Storage**: **service (distribution) reservoirs** absorb hourly fluctuations so that the pumps and treatment plant can run at a uniform rate. They maintain pressure, provide fire reserve and breakdown storage, and reduce pipe sizes. Types: surface (ground-level, ESR fed from it) and elevated (ESR / overhead tank).
- **Total storage capacity** = **balancing (equalising) storage** + breakdown storage + fire reserve. Balancing storage is found by the **mass curve** method (sum of maximum surplus and maximum deficit), or analytically from the hourly demand table.
- **Balancing reservoirs** located at the far end of a system receive water during low demand and supply it during peak demand. This keeps pressure even.
- **Minimum residual pressure at ferrule point** (CPHEEO): **7 m** for single storey, **12 m** for two storeys, **17 m** for three storeys. Taller buildings use booster pumps and sumps. Fire hydrants need about 100–150 kN/m².

Pipe	Key facts
Cast iron (CI) – spun/centrifugally cast	Corrosion resistant, long life (≈ 100 yr), but **brittle** and heavy. Bell-and-spigot joint (lead caulked) or flanged
Ductile iron (DI) – IS 8329	Stronger and tougher than CI; classes K7, K9. **Push-on (Tyton) rubber gasket** joint. Now the most common for mains
Mild steel (MS)	Large-diameter, high-pressure mains (penstocks). Light but needs lining and coating (corrodes). Welded joints
Prestressed concrete (PSC) / PCCP	Large-diameter trunk mains; no corrosion; heavy
uPVC / PVC	Light, smooth (C ≈ 150), corrosion-free, cheap. Weak under UV/sunlight and heat. Solvent-cement or rubber-ring joints
HDPE	Flexible, coiled lengths. **Butt-fusion / electrofusion** welding. Suits house connections and rural schemes

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Asbestos cement (AC)	Light, corrosion resistant, brittle. **Simplex coupling** joint. Now discouraged (asbestos)
GI	House plumbing; threaded and socketed joints

- **Joints**: **spigot & socket (bell & spigot)** for CI; **flanged** joints at pumps, valves and meters (rigid, dismantlable); **mechanical (Dresser coupling)**; **flexible (ball-and-socket)** joints at **river crossings** and settlement zones; **expansion joints** on exposed steel pipes; Simplex joints for AC.

Valve	Function / location
Sluice (gate) valve	Stops or regulates flow and divides mains into sections for repairs. The most common type
Check / reflux / non-return valve	Allows flow in **one direction only**. Placed on the **pump delivery** pipe to prevent backflow when the pump stops
Air relief valve	At **summits (high points)**. Releases accumulated air and admits air when the main is emptied
Pressure relief (safety) valve	Opens automatically when pressure exceeds a set value (protects against water hammer)
Pressure-reducing valve (PRV)	Reduces pressure for low-lying zones
Scour / blow-off / drain valve	At the **lowest points (depressions)**. Drains and flushes sediment
Altitude valve	Prevents an elevated tank from overflowing
Foot valve	At the end of the pump suction pipe (non-return + strainer); keeps the pump primed
Butterfly valve	Throttling on large mains; compact

KEY FORMULAE – PIPE HYDRAULICS

- Darcy–Weisbach: $h_f = f\,L\,V^2 / (2\,g\,D)$ (with $f = 4f'$; laminar $f = 64/Re$)
- **Hazen–Williams** (most used for water mains): $V = 0.849\,C\,R^{0.63}\,S^{0.54}$ (SI); C ≈ 130 (new CI), 140–150 (PVC/HDPE)
- Manning: $V = (1/n)\,R^{2/3}\,S^{1/2}$
- **Hardy Cross** (loops): correction $\Delta Q = -\Sigma\, r\,Q|Q|^{n-1} / (n\,\Sigma\, r\,|Q|^{n-1})$; n = **1.85** (Hazen–Williams) or **2** (Darcy). It balances **heads** (method of balancing heads) with corrections on assumed flows. The other method, balancing flows, assumes heads
- Water hammer (sudden closure, $t \le 2L/c$): $\Delta p = \rho\,c\,V$ (Joukowsky); c ≈ 1000–1400 m/s in pipes
- Economical velocity in mains ≈ 0.6–2 m/s (commonly 1–1.5 m/s)

- **Leak detection**: direct observation, sounding rods, **aquaphone / listening sticks**, **waste detection meters (Deacon meter)** that record night flow, district metered areas (DMA), pressure tests, acoustic correlators, tracer gases.

- **Water meters**: **positive displacement** (piston/disc; accurate at low flow; domestic) and **inferential / velocity** (rotary, turbine, **Woltmann** for bulk). Venturi meters and electromagnetic flow meters are used for mains.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Layout best suited to a town with a rectangular street pattern? → **Grid-iron system**.
- Valve provided at summits of a pipeline? → **Air relief valve**; at the lowest points → **scour valve**.
- Valve on the delivery side of a pump to prevent backflow? → **Reflux (check) valve**.
- In the Hardy Cross method using Hazen–Williams, n = ? → **1.85**.
- Minimum residual pressure for a 3-storey building (CPHEEO)? → **17 m**.

9.5 Sewage Systems & Characteristics ★★★

- **Terms**: **sewage** = liquid waste (sullage + night soil + industrial). **Sullage** = wastewater from kitchens and baths without faecal matter. **Sewer** = conduit that carries sewage. **Sewerage** = the whole system of collection, conveyance and disposal.
- **Conservancy system** = old manual collection of night soil (now prohibited). **Water-carriage system** = modern sewer system.

System	Features
Separate system	Sanitary sewage and storm water are carried in separate conduits. Sewers are small and self-cleansing; treatment load is smaller; pumping is cheaper. Two sets of pipes are needed. **Preferred in India** (CPHEEO)
Combined system	One conduit carries both. Sewers are large, so self-cleansing velocity is hard to achieve in dry weather; overflows (CSOs) pollute streams; treatment load is large. Rainfall flushes the sewer. Used in old cities and where rainfall is uniform
Partially separate	Part of the storm water (from roofs and courtyards) is admitted into the sanitary sewer

- **Dry weather flow (DWF)** = sanitary sewage without storm water. DWF ≈ **80%** of the water supplied (CPHEEO; 75–80% in textbooks), plus infiltration allowance and industrial flow.
- **Peak factor for sewage** (CPHEEO 2013): population up to 20,000 → **3.0**; 20,000–50,000 → 2.5; 50,000–7.5 lakh → 2.25; above 7.5 lakh → **2.0**. Minimum flow ≈ 1/3 to 1/2 of average.
- **Storm water** is estimated by the **rational method**. Time of concentration = **time of entry (inlet time) + time of flow**. Design rainfall intensity is taken for a duration equal to t_c. Return period: about 1–2 years for residential areas and 2–5 years for commercial/high-value areas (CPHEEO). Empirical formulae: Dicken, Ryve, Inglis (catchment), and the British Ministry of Health formula for intensity.

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KEY FORMULAE – SEWER DESIGN

- **Rational formula**: Q = C I A / 360 (Q m^3/s, I mm/h, A ha) or Q = 2.78 C I A (L/s, A in ha)
- Manning: V = (1/n) $R^{2/3}$ $S^{1/2}$; for a circular pipe running full, R = D/4
- **Self-cleansing velocity (Shields / Camp)**: V_s = (1/n) $R^{1/6}$ √[k′ (G_s − 1) d]; k′ = 0.04 (clean inorganic grit) to 0.8 (sticky organic)
- Circular sewer (constant n): **half-full** → V = V_{full}, Q = Q_{full}/2. **Maximum velocity at d ≈ 0.81 D**, **maximum discharge at d ≈ 0.94 D**
- Rule of thumb: the sewer-design velocity at ultimate peak flow is reached when d/D ≤ 0.8 (CPHEEO 2013)

- **Self-cleansing velocity** = the minimum velocity that prevents deposition of solids: **0.6 m/s** (at present peak flow) to **0.8 m/s** (at ultimate peak flow) for sanitary sewers (CPHEEO). Storm and combined drains: **0.75–1.0 m/s** (grit). The textbook range for sewers is 0.6–0.9 m/s.
- **Maximum (non-scouring) velocity** limits erosion of the sewer. CPHEEO generally limits it to **3.0 m/s**.
- **Minimum sewer diameter**: **150 mm** for public sewers (CPHEEO). House drains are 100 mm.
- **Design depth**: sewers are designed to run partially full, at most **0.8 D** at ultimate peak (older practice: half full for D ≤ 0.4 m, ¾ full for larger sizes). The partial flow leaves room for ventilation.
- Sewer gradients are flatter for larger sizes. Sewers are laid from **downstream to upstream** (outfall first).

Sewer material	Max. non-scouring velocity (m/s, approx.)	Manning's n (typical)
Earthen channel	0.6–1.2	0.02–0.025
Brick-lined / brick masonry	1.5–2.5	0.015–0.017
Cement concrete / RCC	2.5–3.0	**0.013** (0.011–0.015)
Cast iron	3.5–4.5	0.012–0.013
Stoneware / **vitrified (salt-glazed)**	**4.5–5.5** (highest)	0.011–0.013
PVC / HDPE / GRP	≈ 3–6	0.009–0.011

- **Sewer shapes**: circular (most common: maximum hydraulic mean depth per area, strong, economical); **egg-shaped (ovoid)** gives a **higher velocity at low flows** and is used in **combined sewers** with widely varying flow, but is difficult to build and less stable (needs a strong foundation); horseshoe, semi-elliptical, U-shaped, rectangular, basket-handle.
- **Materials**: **salt-glazed stoneware (SW)** for small sizes (≤ 600 mm). It is highly resistant to H_2S/acid corrosion and abrasion, but brittle. **RCC (NP2, NP3, NP4 classes, IS 458)** for large sizes. CI for crossings and pressure mains. PVC, HDPE, DWC (double-wall corrugated) and GRP for modern sewers. Brick masonry is used for very large combined sewers.

Appurtenance	Key facts
Manhole	Access for inspection and cleaning. Provided at every **change of direction, gradient or diameter**, at junctions, and at intervals on straight runs. Shallow (0.7–0.9 m, inspection chamber), normal (≈ 1.5 m) and deep. Minimum width = sewer diameter + 150 mm benching on each side. Access opening ≥ 560 mm
Manhole spacing (IS 1742 / CPHEEO)	Small sewers (≤ 0.3 m): ≈ 30–45 m; 0.9–1.5 m dia: 90–150 m; 1.5–2.0 m: 150–200 m; > 2.0 m: **300 m**. Rule for very large sewers: ≈ **100 m per 1 m diameter**
Drop manhole	Where a branch sewer enters a main at a much higher level: **difference in invert > 0.6 m**. Prevents splashing and protects workers
Lamp hole	Vertical shaft for lowering a lamp to inspect the sewer between manholes, used where a manhole is not justified
Clean-out	Inclined pipe at the head of a lateral sewer, used for flushing and rodding
Inverted siphon (depressed sewer)	Carries sewage **below obstacles** (rivers, railways, valleys). Runs **full under pressure**. Velocity ≥ about 0.9–1.0 m/s; usually 2–3 parallel pipes for varying flows
Street inlet / gully	Admits storm water from roads (kerb, gutter, combined inlets)
Catch basin	Storm inlet with a **sump that retains grit** before water enters the sewer
Grease & oil trap	At hotels, restaurants and garages. Grease floats and is retained
Flushing tank	At the heads of sewers where self-cleansing velocity is not achieved (automatic siphon)
Storm regulators	Overflow weirs, leaping weirs, siphon spillways (for combined sewers)

- **Sewer gases**: H_2S (rotten egg; toxic), CH_4 (explosive at 5–15% in air), CO_2, NH_3. Sewers are ventilated through **ventilating columns / vent shafts** and perforated manhole covers.
- **Crown corrosion** of concrete sewers: H_2S released from stale sewage is oxidised by *Thiobacillus* bacteria to **H_2SO_4** on the moist **crown** (above the water line), which attacks the cement. Remedies: proper velocity and ventilation, aeration, chlorination, PVC/HDPE/SW pipes or lining, sulphate-resisting cement.
- **Sewage** is about **99.9% water and 0.1% solids**. Fresh sewage is grey with a musty odour. Stale/septic sewage is **black** and smells of H_2S.
- **Total solids** = suspended + dissolved. **Volatile solids** (lost at 550 °C) ≈ organic. Settleable solids are measured in an **Imhoff cone** (1 h). Typical medium-strength sewage: TS ≈

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700–1000 mg/L, SS ≈ 200–300 mg/L, BOD_5 ≈ 200–300 mg/L.

- **BOD** (biochemical oxygen demand) = oxygen used by microbes to oxidise biodegradable organics aerobically. The standard test is **BOD_5 at 20 °C**. In India, **BOD_3 at 27 °C** (IS 3025 Part 44) is used, and it is ≈ BOD_5 at 20 °C. The test uses a 300 mL BOD bottle and dilution water. **BOD = (D_1 − D_2)/P**, where P = decimal fraction of sample.
- **COD** = oxygen equivalent of organics oxidised chemically by **potassium dichromate** ($K_2Cr_2O_7$) in hot H_2SO_4 with Ag_2SO_4 catalyst, refluxed for 2 h (≈ 3 h). It includes non-biodegradable organics, so **COD > BOD**. Permanganate value (OA test) uses $KMnO_4$, 4 h at 27 °C.
- **TOC** = total organic carbon, measured by combustion and CO_2 detection. **ThOD** = theoretical oxygen demand from the chemical formula (stoichiometric).
- Typical order: **ThOD > COD > BOD_u > BOD_5 > TOC** (in mg/L). Biodegradability index **BOD_5/COD**: ≈ 0.4–0.6 for domestic sewage; > 0.5 means readily biodegradable; < 0.3 means needs chemical/physical treatment.
- **First-stage BOD** (carbonaceous) is exerted first. **Second-stage (nitrification) BOD** starts after about 6–10 days at 20 °C. Nitrification inhibitors (TCMP/ATU) are used to measure carbonaceous BOD only.
- **DO saturation**: ≈ **14.6 mg/L at 0 °C, ≈ 9.1–9.2 mg/L at 20 °C**, ≈ 7.6 mg/L at 30 °C. It decreases with rising temperature and salinity.
- **Population equivalent** = industrial BOD load (kg/d) ÷ per-capita BOD. The standard textbook value is **0.08 kg BOD_5/person/day (80 g)**; Indian design values are lower (CPHEEO ≈ 27–50 g/capita/day, commonly 45 g).
- **C/N ratio**: about 15–20 for sewage solids. A ratio of 25–30 is optimum for anaerobic digestion and composting. **BOD : N : P = 100 : 5 : 1** is required for aerobic biological treatment.
- **Relative stability** = % ratio of available oxygen to oxygen needed to satisfy first-stage BOD. It is found by the **methylene blue** test: $S = 100\,(1 - 0.794^{t_{20}})$, where t_{20} = days to decolourise at 20 °C.

KEY FORMULAE – BOD KINETICS (FIRST ORDER)

- BOD remaining: $L_t = L_0\,e^{-kt} = L_0\,10^{-Kt}$
- BOD exerted: $y_t = L_0(1 - e^{-kt})$; L_0 = ultimate first-stage BOD
- k (base e) = **2.303 K** (base 10). At 20 °C, typical **$k = 0.23\ d^{-1}$** ($K = 0.1\ d^{-1}$)
- With k = 0.23: $BOD_5/L_0 = 1 - e^{-1.15} \approx$ **0.68** (≈ 2/3)
- Temperature correction: $k_T = k_{20}\,\theta^{(T-20)}$, θ ≈ **1.047** (1.056 for 20–30 °C; 1.135 for 4–20 °C)
- Ultimate BOD is the same at all temperatures; only the rate changes

MEMORY TRICK

"**0.23 → 0.68**": a k of 0.23/day means 68% of ultimate BOD is exerted in 5 days. For self-cleansing velocity: "**Point six, point eight, no deposit**" (0.6 m/s present peak, 0.8 m/s ultimate peak).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Sewer shape best suited to widely varying (combined) flows? → **Egg-shaped**.
- Drop manhole is provided when the difference in invert levels exceeds? → **0.6 m**.
- Crown corrosion of concrete sewers is caused by? → **H_2SO_4 formed from H_2S**.
- Ratio BOD_5/BOD_u for k = 0.23/day? → **≈ 0.68**.
- In a circular sewer, maximum discharge occurs at depth? → **≈ 0.94 D**.
- Population equivalent is based on per-capita BOD of? → **0.08 kg/day**.

9.6 Sewage Treatment ★★★

- **Stages**: preliminary (screens, grit chamber, skimming tank) → **primary** (primary sedimentation; ≈ **30–35% BOD** and **50–70% SS** removal) → **secondary / biological** (ASP, trickling filter, ponds; total BOD removal ≈ **85–95%**) → **tertiary** (nutrient removal, filtration, disinfection, reuse).
- **Screens**: coarse (≥ 50 mm openings), medium (≈ 20–50 mm) and fine (< 10 mm). Bars are inclined at about 30–60° to the horizontal. Velocity through the screen should not exceed about **0.8–1.0 m/s** at peak flow. Comminutors shred solids instead of removing them.
- **Grit chamber** removes inorganic grit (sand, d ≥ **0.2 mm**, G_s ≈ 2.65) and lets organic matter pass. Horizontal velocity is kept nearly constant at about **0.3 m/s** (0.15–0.3 m/s) by a **proportional flow weir (Sutro weir)** or a **Parshall flume** at the outlet. Detention 30–60 s. Aerated and vortex grit chambers are other types.
- **Skimming tank** removes oil, grease and floating matter (fat and soap). Air is blown in, and detention is about **3–5 min**.
- **Primary clarifier**: detention ≈ **2 h**, SOR ≈ 30–40 $m^3/m^2/d$ (avg), weir loading ≤ about 125–185 $m^3/m/d$.

ASP parameter	Conventional ASP	Extended aeration
F/M ratio (kg BOD/kg MLVSS/d)	**0.2–0.4**	**0.05–0.15**
MLSS (mg/L)	**1500–3000**	3000–5000
HRT (aeration period)	**4–8 h** (≈ 6 h)	18–36 h (≈ 24 h)
SRT / MCRT (sludge age)	**5–15 d**	20–30 d
Recirculation ratio Q_r/Q	0.25–0.5	0.5–1.5
Volumetric loading (kg BOD/m^3/d)	0.3–0.7	0.1–0.4
BOD removal	85–95%	95–98%

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KEY FORMULAE – ACTIVATED SLUDGE PROCESS

- **F/M** = $Q\ S_0 / (V\ X)$ (X = MLSS or MLVSS)
- HRT $\theta = V/Q$; volumetric loading = $Q\ S_0 / V$
- **Sludge age (SRT, θ_c)** = $V\ X / [Q_w\ X_r + (Q - Q_w)\ X_e] \approx V\ X / (Q_w\ X_r)$
- **SVI** (mL/g) = settled sludge volume after 30 min (mL/L) × 1000 / MLSS (mg/L). Good settling: **50–150**; **> 200 → bulking**
- Recirculation ratio: $Q_r/Q = X / (X_r - X)$; $X_r \approx 10^6/SVI$
- Oxygen requirement ≈ 1–1.5 kg O_2/kg BOD removed. DO in aeration tank ≥ 1–2 mg/L

- **ASP** is a **suspended-growth aerobic** process (Ardern & Lockett, 1914). Return activated sludge (RAS) keeps MLSS high, and excess sludge is wasted (WAS).
- **Sludge bulking**: the sludge settles poorly (high SVI) because of **filamentous organisms** (*Sphaerotilus natans*, Nocardia). Causes: low DO, low F/M, nutrient (N, P) deficiency, low pH, septic sewage. Remedies: **chlorination or H_2O_2 dosing of RAS**, more aeration, nutrient addition, a selector.
- **Rising sludge**: sludge floats in the secondary clarifier because of **denitrification** (N_2 bubbles).
- **Modifications**: tapered aeration, **step aeration** (sewage fed at several points), **complete-mix** (resists shock loads), contact stabilisation, high-rate, pure-oxygen, extended aeration (no primary clarifier, little sludge, suits small flows).
- **Oxidation ditch (Pasveer ditch)**: extended aeration in an oval racetrack channel, about 1–1.5 m deep, aerated by **cage rotors / brush aerators**. HRT 12–24 h, SRT 20–30 d. Simple, with little sludge.
- **SBR (sequencing batch reactor)**: one tank operated in cycles: **fill → react → settle → draw (decant) → idle**. No separate clarifier.
- **MBBR (moving bed biofilm reactor)**: free-floating plastic carriers (≈ 50–70% fill) carry attached biofilm in an aerated tank. It combines suspended and attached growth and is compact.
- **MBR (membrane bioreactor)**: ASP plus **micro/ultrafiltration membranes** (≈ 0.04–0.4 µm) instead of a secondary clarifier. MLSS 8000–12,000 mg/L, very high effluent quality (reuse grade), small footprint. Drawbacks: membrane fouling and high energy use.
- **UASB (upflow anaerobic sludge blanket)** (Lettinga, Netherlands): anaerobic; sewage flows up through a granular sludge blanket. A **three-phase (gas–liquid–solid) separator** sits at the top. HRT ≈ 8–10 h for sewage, upflow velocity ≈ 0.5–1 m/h. It produces biogas, needs no aeration energy and makes little sludge, but needs **post-treatment** (polishing pond / aerobic step) because effluent BOD is still high. India's first UASB was at **Kanpur (Jajmau), 1989**, under the Ganga Action Plan.

Feature	Standard (low-rate) trickling filter	High-rate trickling filter
Hydraulic loading ($m^3/m^2/d$)	**1–4**	**10–40**
Organic loading (kg BOD/m^3/d)	**0.08–0.32**	**0.32–1.0** (up to ≈ 1.8)
Depth of filter media	1.8–3.0 m	0.9–2.5 m
Recirculation	Generally **none**	**Always** (R = 1–3)
Media size	25–75 mm stone	Larger stone (50–75 mm) / plastic
Sloughing	Intermittent	Continuous
Effluent	Highly **nitrified**	Nitrified only at low loading
Filter flies (*Psychoda*), odour	Common	Rare
BOD removal	**80–90%**	75–90% (two-stage)
Land requirement	Large	Smaller

KEY FORMULAE – TRICKLING FILTER (NRC, AT 20 °C)

- First stage: $E = 100 / [1 + 0.4432\ \sqrt{(W / (V\ F))}]$; E in %, W = BOD load (kg/d), V = media volume (m^3)
- Recirculation factor: $F = (1 + R) / (1 + 0.1\ R)^2$; $R = Q_R/Q$
- Second stage: $E_2 = 100 / [1 + (0.4432 / (1 - E_1))\ \sqrt{(W' / (V\ F))}]$
- A trickling filter is an **attached-growth aerobic** process; the "filter" does no filtering. Rotary distributors spread the sewage

- **Oxidation (waste stabilisation) pond**: a facultative pond where **bacteria and algae live in symbiosis** (algae supply O_2; bacteria supply CO_2 and nutrients). Depth ≈ **1–1.5 m**, detention ≈ **15–30 d** (more in cold climates). Organic loading ≈ 150–350 kg BOD/ha/d (higher at lower latitudes, i.e. south India). Cheap, but needs large land and the effluent contains algae.
- Pond types: **anaerobic** (2.5–5 m deep, 1–5 d), **facultative** (1–2 m), **maturation** (≈ 1–1.5 m; pathogen removal).
- **Aerated lagoon**: mechanically aerated pond, 2.5–5 m deep, HRT 3–6 d (up to 10 d). Needs less land than a stabilisation pond.
- **Septic tank** (IS 2470 Part 1:1985): a horizontal-flow sedimentation and anaerobic digestion tank for houses and institutions not connected to sewers.
  - **Detention time 24 h** (12–72 h). L : B = 2:1 to 4:1, minimum width 750 mm, liquid depth 1–1.8 m, free board ≈ 300 mm.
  - Allow about **0.03 m^3 of sludge per capita per year**. **Desludging** every 1–3 years (about 6 months to 2 years in practice), always leaving some sludge as seed.
  - Removes about 50–70% SS and 30–50% BOD. Effluent is septic and goes to a **soak pit** (seepage pit), **dispersion**

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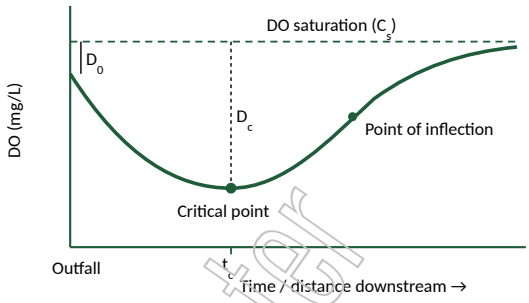
trench or upflow filter.

- Place the tank and soak pit at least about **15–18 m** from any well or water source. Twin-pit pour-flush latrines (SBM) are the low-cost alternative.

- **Imhoff tank** (Karl Imhoff): a **two-storey** tank. The upper sedimentation chamber has a 2–4 h detention. The lower digestion chamber is connected by a slot, so **fresh sewage and digesting sludge do not mix**. Gas vents are provided. The effluent is not septic, unlike a septic tank's.
- **Sludge**: primary sludge ≈ 93–97% water. Activated (secondary) sludge ≈ 98–99.5% water.
- Volume–moisture relation: $\mathbf{V_1/V_2 = (100 - p_2)/(100 - p_1)}$. For example, thickening from 98% to 96% moisture halves the volume.
- **Treatment sequence**: thickening (gravity thickener; DAF for activated sludge) → stabilisation (anaerobic/aerobic digestion, lime) → conditioning (chemicals/heat) → dewatering (**sludge drying beds**, centrifuge, belt press, filter press, vacuum filter) → disposal (land application, landfill, incineration).
- **Anaerobic digestion** stages: **hydrolysis → acidogenesis (acid fermentation / liquefaction) → acetogenesis → methanogenesis** (gasification). Methanogens are slow-growing and pH-sensitive, so the optimum pH is **6.8–7.2** (range 6.5–7.5). Volatile acids/alkalinity < 0.3–0.4.
- **Mesophilic digestion**: **30–38 °C** (≈ 35 °C), digestion time ≈ 25–30 d (standard rate up to 30–60 d). **Thermophilic**: **50–57 °C** (≈ 55 °C), ≈ 10–15 d, with better pathogen kill.
- **Digester gas**: CH_4 65–70%, CO_2 25–30%, traces of H_2S. Calorific value ≈ 22–26 MJ/m³ (≈ 5300–6000 kcal/m³).
- **Sludge drying beds**: sand about 20–30 cm over gravel, with under-drains. Sludge is applied 20–30 cm deep and dries in about 1–2 weeks in dry weather. Dried cake has about 60–70% moisture.
- **Disposal by dilution** into rivers, lakes or sea. Dilution factor guide (textbook): **> 500** → no treatment; 300–500 → primary (plain sedimentation); 150–300 → sedimentation, screening and chemical precipitation; **< 150** → complete treatment.
- **Self-purification** of streams results from dilution, sedimentation, oxidation (aerobic decay), reduction (anaerobic decay), **sunlight** (algae photosynthesis, bactericidal), temperature and turbulence (reaeration). Higher temperature speeds decay but lowers saturation DO.
- **Oxygen sag curve (Streeter–Phelps, 1925)**: the DO profile below an outfall results from **deoxygenation** (BOD exertion, k_1) and **reaeration** (k_2, atmospheric). The lowest DO is at the **critical point**. The **point of inflection** beyond it is where the rate of recovery is maximum.
- **Zones of pollution** (Whipple): **zone of degradation** (just below the outfall: turbid, DO falling, fungi) → **zone of active decomposition** (DO minimum, may be zero; anaerobic, gas bubbles, black; fish absent) → **zone of recovery** (DO rises; algae, fish reappear) → **zone of clear water** (natural conditions).



Oxygen sag curve: deficit $D = C_s - DO$. Minimum DO (critical deficit D_c) occurs at time t_c.

KEY FORMULAE – STREETER–PHELPS (BASE E)

- Deficit: $\mathbf{D_t = [k_1L_0/(k_2 - k_1)]\,(e^{-k_1t} - e^{-k_2t}) + D_0\,e^{-k_2t}}$
- Critical time: $t_c = [1/(k_2 - k_1)]\,\ln\{(k_2/k_1)\,[1 - D_0(k_2 - k_1)/(k_1L_0)]\}$
- Critical deficit: $\mathbf{D_c = (k_1/k_2)\,L_0\,e^{-k_1t_c}}$
- **Self-purification constant $f = k_2/k_1$** (= reaeration / deoxygenation); f ≈ 0.5–1 for small ponds, 1–1.5 for sluggish streams, 3–5 for swift streams, > 5 for rapids (Fair)
- Mixed concentration: $C = (Q_sC_s + Q_rC_r)/(Q_s + Q_r)$

- **Land disposal / sewage farming**: sewage (preferably settled) is used for irrigation on sandy or loamy soils. Fertilising value: N, P, K.
- **Sewage sickness**: continuous application clogs the soil pores, which become anaerobic and give off foul gases (H_2S). Prevention: **primary treatment first**, resting the land, rotating crops and plots, under-drains, shallow and intermittent application, breaking up the surface.

CPCB general standards (EPA Rules 1986, Sch. VI)	Inland surface water	Public sewers	Land for irrigation	Marine coastal
BOD (3 d, 27 °C), mg/L	**30**	350	100	100
Total suspended solids, mg/L	**100**	600	200	100
COD, mg/L	**250**	–	–	250
pH	**5.5–9.0**	5.5–9.0	5.5–9.0	5.5–9.0
Oil & grease, mg/L	**10**	20	10	20

- Other inland surface water limits: temperature ≤ 5 °C above the receiving water; residual chlorine 1.0 mg/L; ammoniacal-N 50 mg/L; Cr^{6+} 0.1 mg/L; Hg 0.01 mg/L.

CPCB designated best-use class of water	DO (min)	BOD (max)	Total coliform (MPN/100 mL)

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A – drinking without conventional treatment, after disinfection	6	2	≤ 50
B – outdoor bathing	5	3	≤ 500
C – drinking after conventional treatment	4	3	≤ 5000
D – propagation of wildlife, fisheries	4	–	– (free NH_3 ≤ 1.2)
E – irrigation, industrial cooling	EC ≤ 2250 µS/cm, SAR ≤ 26, boron ≤ 2 mg/L		

CODE UPDATE

MoEFCC notification (Oct 2017) set discharge norms for **STPs**: BOD ≤ **30 mg/L** (≤ 20 in metro cities and state capitals), TSS < 100 (< 50 in metros), pH 6.5–9.0, faecal coliform < 1000 MPN/100 mL. NGT (2019) later directed stricter norms (BOD 10, COD 50, TSS 20, TN 10, TP 1 mg/L). The **CPHEEO Manual on Sewerage & Sewage Treatment Systems, 2013** replaced the 1993 manual.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Velocity maintained in a grit chamber? → **≈ 0.3 m/s** (kept constant by a proportional flow weir / Parshall flume).
- Sludge bulking is indicated by SVI greater than? → **≈ 200 mL/g** (normal 50–150).
- Trickling filter with recirculation always provided? → **High-rate trickling filter**.
- Detention period of a septic tank? → **24 h**.
- The lowest point of the oxygen sag curve is called? → **Critical point**.
- BOD limit for discharge into inland surface water (CPCB)? → **30 mg/L** (TSS 100 mg/L).

9.7 Air Pollution ★★★

- **Composition of dry air** (by volume): N_2 **78.08%**, O_2 **20.95%**, Ar 0.93%, CO_2 ≈ 0.04% (≈ 420 ppm and rising), Ne, He, CH_4 in traces.
- **Sources**: **stationary point** (power plants, industries), **area** (residential burning) and **mobile/line** (vehicles). Also natural vs anthropogenic.
- **Primary pollutants** are emitted directly: SO_2, NO (most NO_x), CO, hydrocarbons/VOCs, particulates, Pb, NH_3. **Secondary pollutants** form in the atmosphere: **O_3 (tropospheric), PAN**, aldehydes, H_2SO_4/HNO_3 mist, sulphate/nitrate aerosols, photochemical smog.

Pollutant	Main sources	Effects / key facts
CO	Incomplete combustion; **vehicles** (largest source)	Affinity for haemoglobin ≈ **200–250 × that of O_2**, forming **carboxyhaemoglobin (COHb)** and causing asphyxia. Colourless and odourless
SO_2	Coal/oil combustion (thermal power plants), smelters, refineries	Respiratory irritant, acid rain, **"stone leprosy"** of marble (Taj Mahal). **Lichens** are indicators of SO_2. Chlorosis in plants
NO_x	High-temperature combustion (vehicles, power plants)	NO_2 is reddish-brown and a lung irritant; precursor of O_3, PAN and acid rain
O_3 (ground-level)	Secondary: NO_x + VOC + sunlight	Respiratory irritant, crop damage, rubber cracking
PAN (peroxyacetyl nitrate)	Secondary (photochemical smog)	**Eye irritation**, toxic to plants
PM_{10} / $PM_{2.5}$	Dust, combustion, construction, stubble burning	$PM_{2.5}$ (fine) reaches the **alveoli**. Visibility reduction
Lead (Pb)	Formerly leaded petrol (TEL, phased out in India by 2000), batteries, smelters	Neurotoxic, anaemia, affects children's IQ
VOCs / **benzene**; benzo(a)pyrene	Petrol evaporation, solvents; incomplete combustion	Benzene → **leukaemia** (carcinogen); BaP (a PAH) → lung cancer
Methyl isocyanate (MIC)	**Bhopal gas tragedy**, 2–3 Dec 1984 (Union Carbide)	Acute lung damage, deaths

- **Occupational lung diseases**: silicosis (silica, stone quarries), asbestosis (asbestos), **anthracosis / black lung** (coal dust), **byssinosis** (cotton dust, brown lung), siderosis (iron), bagassosis (sugarcane bagasse), farmer's lung (mouldy hay).

Feature	Photochemical smog (Los Angeles type)	Classical / London smog (1952)
Chemical nature	**Oxidising**	**Reducing**
Main constituents	NO_x, hydrocarbons → **O_3, PAN**, aldehydes	**SO_2 + smoke (soot) + fog**
Season / time	**Summer**, sunny, around noon–afternoon	**Winter**, early morning, cold humid
Weather	Bright sunlight, low humidity, subsidence inversion	Fog, calm air, radiation inversion
Colour / effect	Brownish haze; eye irritation, plant damage	Grey-black; bronchial irritation, high mortality

- **Greenhouse gases**: water vapour (most abundant natural GHG), **CO_2** (largest anthropogenic contribution), CH_4, N_2O, O_3, CFCs/HFCs, SF_6. The **Kyoto Protocol** (1997) covers six gases: CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 (NF_3 was added in

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2012). **Paris Agreement** (2015): keep warming well below 2 °C, pursuing 1.5 °C.

- **Global warming potential** (100-yr, IPCC AR5): CO_2 = **1**, CH_4 ≈ **28** (AR6: 27–30; older textbook 21), N_2O ≈ **265** (older 310; AR6 273), HFC-134a ≈ 1300, **SF_6 ≈ 23,500 (the highest)**.
- **Acid rain** = rain with **pH < 5.6**. Normal rain is about 5.6 because of dissolved CO_2 (carbonic acid). Acid rain is mainly **H_2SO_4 (≈ 60–70%)** and HNO_3 (≈ 30%). It damages lakes (fish), forests and monuments.
- **Ozone layer**: in the stratosphere (≈ 15–35 km); it absorbs UV-B. It is measured in **Dobson units**, and an ozone hole is < 220 DU (over Antarctica in spring). **CFCs** release Cl radicals, and one Cl atom can destroy about 10^5 O_3 molecules. Halons (Br) and CCl_4 also deplete it.
- **Vienna Convention** 1985 → **Montreal Protocol 1987** (phase-out of ODS) → **Kigali Amendment 2016** (phase-down of HFCs). World Ozone Day: **16 September**.
- **Lapse rate** = rate of fall of temperature with height.
  - **Environmental lapse rate (ELR)** is the actual value; the standard atmosphere uses **6.5 °C/km**.
  - **Dry adiabatic lapse rate (DALR)** = **9.8 °C/km** (≈ 1 °C/100 m).
  - **Wet (saturated) adiabatic** rate ≈ 4–7 °C/km (≈ 6 °C/km).
- **Stability** (with lapse rates taken as positive values):
  - **ELR > DALR → super-adiabatic → unstable** (strong vertical mixing).
  - ELR = DALR → **neutral**.
  - **ELR < DALR → sub-adiabatic → stable**.
  - Temperature increasing with height (negative lapse rate) = **inversion**, which is extremely stable.
- **Inversions**: **radiation inversion** (ground cools at night; clear calm nights; breaks up in the morning), **subsidence inversion** (sinking air in high-pressure systems; aloft; long-lasting; Los Angeles), frontal and advective inversions.
- **Maximum mixing depth (MMD)** = height up to which convective mixing occurs. It is lowest at night and in winter, so pollution episodes are worse in winter.

Plume type	Atmospheric condition	Remarks
Looping	**Super-adiabatic (highly unstable)**; sunny day, light wind	Wavy plume. High ground-level concentrations close to the stack, intermittently
Coning	**Neutral / slightly stable** (sub-adiabatic close to neutral); cloudy, windy	Cone shape. Fits the Gaussian dispersion model best
Fanning	**Inversion / strongly stable** at all levels (night)	Spreads horizontally with little vertical mixing; fan shape in plan
Lofting	**Inversion below**, unstable/neutral above stack top	Pollutants carried upward, not down. **Most favourable** (least ground-level concentration)
Fumigation	**Unstable below**, inversion above stack top (morning break-up)	Pollutants brought down to the ground. **Most harmful / worst**
Trapping	Inversion **above and below** the stack	Plume trapped between the two inversion layers

MEMORY TRICK

Plume order from unstable to stable: "**L-C-F**" = **L**ooping (unstable), **C**oning (neutral), **F**anning (inversion). For mixed conditions: "**L**ofting is **L**ucky (goes up), **F**umigation is **F**atal (comes down)".

NAAQS 2009 (CPCB, 18 Nov 2009) – 12 pollutants	Time-weighted average	Industrial, residential, rural & other areas	Ecologically sensitive area
SO_2 (µg/m³)	Annual / 24 h	**50 / 80**	20 / 80
NO_2 (µg/m³)	Annual / 24 h	**40 / 80**	30 / 80
PM_{10} (µg/m³)	Annual / 24 h	**60 / 100**	60 / 100
$PM_{2.5}$ (µg/m³)	Annual / 24 h	**40 / 60**	40 / 60
O_3 (µg/m³)	8 h / 1 h	**100 / 180**	100 / 180
Lead (µg/m³)	Annual / 24 h	0.5 / 1.0	0.5 / 1.0
CO (mg/m³)	8 h / 1 h	**2 / 4**	2 / 4
NH_3 (µg/m³)	Annual / 24 h	100 / 400	100 / 400
Benzene (µg/m³)	Annual	5	5
Benzo(a)pyrene (ng/m³)	Annual	1	1
Arsenic / Nickel (ng/m³)	Annual	6 / 20	6 / 20

- The 2009 NAAQS added $PM_{2.5}$, O_3, NH_3, benzene, BaP, As and Ni, and merged the old industrial and residential categories into one. Ecologically sensitive areas have stricter limits only for SO_2 and NO_2 (annual).

National AQI (launched 2014; 8 pollutants)	AQI range	$PM_{2.5}$ 24 h (µg/m³)	PM_{10} 24 h (µg/m³)
Good	**0–50**	0–30	0–50
Satisfactory	51–100	31–60	51–100
Moderately polluted	101–200	61–90	101–250
Poor	201–300	91–120	251–350

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Very poor	301–400	121–250	351–430
Severe	**401–500**	> 250	> 430

- AQI pollutants: PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, NH_3, Pb. At least 3 pollutants are needed, one of which must be PM_{10} or $PM_{2.5}$. The overall AQI is the **maximum sub-index**, not the average.

Particulate control device	Particle size range	Efficiency / remarks
Gravity settling chamber	**> 50 µm**	Low efficiency; low cost and pressure drop. Used as a **pre-cleaner**
Cyclone (centrifugal)	**> 5–10 µm**	50–90%. Efficiency rises with inlet velocity and particle size, and falls as cyclone diameter increases. Cut size d_{50}. No moving parts
Fabric filter (baghouse)	**> 0.1–1 µm**	**> 99%**. Limited by temperature (≈ 250–280 °C) and moisture/sticky dust. Cleaned by shaking, reverse air or pulse jet. Air-to-cloth ratio
Electrostatic precipitator (ESP)	**0.01/0.1 – 10 µm**	**99–99.9%**. Very low pressure drop; handles hot gases and large volumes; high capital cost; affected by **dust resistivity**. Used for **fly ash in thermal power plants**
Wet scrubbers (spray tower, **venturi**, packed bed)	Venturi: 0.5–5 µm	Venturi up to 99%, with a **high pressure drop**. Also removes gases and cools them. Produces a wastewater sludge

KEY FORMULAE – CONTROL & DISPERSION

- **ESP (Deutsch–Anderson)**: $\eta = 1 - e^{-wA/Q}$; w = drift velocity, A = collecting plate area, Q = gas flow
- **Gaussian plume**: ground-level concentration on the centreline is $\propto Q/(\pi u \sigma_y \sigma_z)\, e^{-H^2/2\sigma_z^2}$; $C_{max} \propto Q/(u H^2)$, and occurs where $\sigma_z = H/\sqrt{2}$
- Effective stack height **H = h_s + Δh** (plume rise by Holland's or Briggs' formula)
- **Stack height (CPCB)**: **$H = 14\, Q^{0.3}$** (Q = SO_2 emission in **kg/h**); $H = 74\, Q^{0.27}$ (Q = particulate emission in t/h). Take the greater value, subject to a **minimum of 30 m**
- DG set stack height: H = h (building height) + **0.2 √kVA**

- **Gaseous pollutant control**:
  - **Absorption**: packed or spray towers. For example, **FGD (flue gas desulphurisation)** scrubs SO_2 with limestone slurry and produces gypsum.
  - **Adsorption**: **activated carbon**, silica gel or alumina for VOCs and odours.
  - **Combustion / incineration**: flare, thermal or **catalytic** incineration of VOCs, CO and odours.
  - Condensation.
- **Vehicles**: the **three-way catalytic converter** (Pt, Pd, Rh) controls CO, HC and NO_x. **Bharat Stage VI** applies nationwide from **1 April 2020** (BS-V was skipped). CNG, EVs and diesel particulate filters are other measures.
- **Air (Prevention & Control of Pollution) Act, 1981**: declares air pollution control areas and requires consent to establish/operate. The **1987 amendment added noise** as an air pollutant. Water Act 1974 (CPCB constituted in 1974); **Environment (Protection) Act 1986** (umbrella act, after Bhopal).
- **NCAP (National Clean Air Programme)**, launched **10 January 2019**, initially targeted a 20–30% cut in PM by 2024 (base 2017). The revised target is **up to 40% reduction in PM_{10}** (or meeting the NAAQS) by **2025–26** in **131 non-attainment cities**. Progress is tracked on the PRANA portal.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Plume type during a super-adiabatic lapse rate? → **Looping**. With inversion above the stack and unstable air below? → **Fumigation**.
- Dry adiabatic lapse rate? → **9.8 °C/km**.
- Most efficient device for sub-micron particulates in thermal power plants? → **ESP**.
- CPCB stack height formula for SO_2? → **$H = 14\, Q^{0.3}$** (Q in kg/h), minimum **30 m**.
- NAAQS 24-h limit for $PM_{2.5}$ / PM_{10}? → **60 / 100 µg/m³**.
- AQI range for the "Severe" category? → **401–500**.

9.8 Municipal Solid Waste ★★★

CODE UPDATE – SWM RULES 2026

MoEFCC notified the **Solid Waste Management Rules, 2026** (under EP Act 1986), **replacing the SWM Rules 2016**, in force from **1 April 2026**. Key changes: segregation into **four streams – wet, dry, sanitary and special-care (domestic hazardous)**; **bulk waste generator** = built-up area > **20,000 m²** OR water use > **40,000 L/day** OR waste > **100 kg/day**; **Extended Bulk Waste Generator Responsibility**; landfill only for non-recyclable, non-energy-recoverable and inert waste; RDF use in industries to rise from **5% to 15%** in six years; mandatory dumpsite mapping and biomining; Polluter Pays via environmental compensation. The 2016 provisions below are kept because older-pattern questions still use them.

- **Solid Waste Management Rules, 2016** (notified 8 April 2016) replaced the **MSW (Management & Handling) Rules, 2000**. They apply beyond municipal areas: census towns, notified industrial townships, railways, airports, SEZs, places of pilgrimage and defence establishments.
- **Segregation at source into three streams**: **biodegradable (wet, green bin)**, **non-biodegradable (dry, blue bin)** and **domestic hazardous waste** (e.g. paint cans, batteries, CFL bulbs, pesticides). Sanitary waste (diapers, pads) is wrapped separately.
- **Other provisions of the 2016 Rules**:

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  - User fee and spot fines.
  - **Bulk waste generators** (e.g. ≥ 100 kg/day) must process wet waste on site as far as possible.
  - Non-recyclable waste with a high calorific value (**≥ 1500 kcal/kg**) goes to waste-to-energy or RDF, not to landfill.
  - **Landfill only for non-usable, non-recyclable, non-biodegradable, non-combustible and non-reactive inert waste** and pre-processing rejects.
  - Industries within 100 km of an RDF plant must use RDF.
- **Indian MSW generation**: about 0.3–0.6 kg/capita/day (higher in large cities; ≈ 0.45 average). Total ≈ 1.5 lakh tonnes per day.
- **Composition of Indian MSW**: compostable/organic **≈ 40–60%** (about 50%), recyclables (paper, plastic, metal, glass) ≈ 15–20%, inerts (ash, grit) ≈ 20–30%.
- **Physical properties of Indian MSW**: moisture ≈ 40–60%, low **calorific value ≈ 800–1100 kcal/kg**, and **high density ≈ 350–550 kg/m³** (uncompacted). Developed countries have ≈ 100–200 kg/m³, with more paper and plastic.
- **Functional elements** (sequence): waste generation → on-site handling, storage & processing → **collection** → transfer & transport → processing & recovery → **disposal**.
- **Collection** is the costliest element, at about **60–80%** of total SWM cost. Door-to-door collection uses compartmentalised vehicles. Hauled container system vs stationary container system. **Transfer stations** are used when the haul distance is large (beyond about 15–20 km).

Processing method	Key facts
Aerobic composting (windrow / in-vessel)	**C/N 25–30** (optimum), moisture 50–60%, temperature rises to **55–65 °C** (thermophilic; ≥ 55 °C kills pathogens), O_2 > 5%, pH 6–8. Windrows are turned periodically. Final compost C/N < 20. Indore method (Howard, aerobic); Bangalore method (Acharya, mainly anaerobic, pits)
Vermicomposting	Earthworms: **Eisenia fetida** (red wiggler), *Eudrilus eugeniae*, *Perionyx excavatus*. Moderate temperature (20–30 °C), moisture ≈ 40–60%. Product: vermicast
Anaerobic digestion / biomethanation	Wet, segregated organic waste (kitchen/market waste) → **biogas (CH_4 55–65%)** + digestate manure
Incineration (mass burning, WtE)	Controlled combustion at ≈ **850–1100 °C**. Volume reduction ≈ 90% (mass ≈ 75%). Needs a **high calorific value and low moisture**, so it is generally **less suitable for Indian MSW**. Dioxins/furans need control
RDF (refuse-derived fuel)	Dry combustible fraction (plastic, paper, textiles) shredded and dried (CV ≈ 3000–4500 kcal/kg). Used in **cement kilns (co-processing)** and power plants
Pyrolysis	Thermal decomposition in the **absence of oxygen**; **endothermic**. Products: char, pyrolytic oil, gas
Gasification	**Partial oxidation** (limited O_2/air) → **syngas (CO + H_2)**. Plasma-arc gasification is a variant

- **Sanitary landfill**: an engineered site where waste is spread in thin layers, **compacted** and **covered with soil daily**, with a liner, leachate collection and gas management. Methods: **area** (flat land), **trench** (deep water table) and **ramp/slope**. Open dumping is not a landfill.
- **Liner system** (SWM/MSW Rules): a composite liner of **1.5 mm HDPE geomembrane** over **90 cm of compacted clay** with **$k \le 1 \times 10^{-7}$ cm/s**, topped by a leachate collection (drainage) layer about 30 cm thick.
- **Cover layers**: **daily cover ≈ 10 cm** of soil; intermediate cover ≈ 40–65 cm. Final cover (top down): vegetative layer ≈ 45 cm over a drainage layer ≈ 15 cm over a barrier soil layer ≈ 60 cm with $k \le 10^{-7}$ cm/s.
- **Leachate** = liquid that percolates through the waste. It has very high BOD and COD (thousands of mg/L), heavy metals and NH_3. It is collected, treated and recirculated.
- **Landfill gas**: **CH_4 ≈ 45–60%** and **CO_2 ≈ 40–50%**, plus traces of NMOCs and H_2S. Methane is explosive at 5–15% in air.
- **Siting criteria** (MSW Rules 2000, carried into 2016):
  - ≥ **100 m from rivers**.
  - ≥ **200 m from ponds, highways, habitations, public parks and water-supply wells**.
  - ≥ **20 km from airports / airbases** (bird hazard).
  - Not in flood plains, wetlands or fault zones. Prefer low-permeability soil with a deep water table.
  - Design life ≈ 20–25 years.

Biomedical Waste Management Rules 2016 – colour code	Waste items	Treatment / disposal
Yellow (non-chlorinated plastic bags)	**Human anatomical waste**, animal waste, **soiled waste** (dressings, cotton, plaster casts), expired/discarded medicines, chemical waste, microbiology & lab waste (pre-treated), discarded linen	**Incineration** plasma pyrolysis / deep burial (rural)
Red (non-chlorinated plastic bags/containers)	**Contaminated recyclable waste**: tubing, bottles, IV tubes and sets, catheters, urine bags, **syringes without needles**, gloves	**Autoclaving / microwaving / hydroclaving** then shredding and recycling (no incineration)

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White (translucent) – puncture-proof, leak-proof, tamper-proof container	**Waste sharps including metals**: needles, syringes with fixed needles, scalpels, blades	Autoclave / dry-heat sterilisation, then shredding / encapsulation / iron foundry
Blue (cardboard boxes with blue marking)	**Glassware** (broken/discarded/contaminated) and **metallic body implants**	Disinfection / autoclaving, then recycling

- Untreated biomedical waste must not be stored beyond **48 h**.
- Bar coding of BMW bags.
- **Chlorinated plastic bags and gloves** are phased out.
- Pre-treatment of lab and highly infectious waste on site.
- BMW incinerator: **primary chamber 800 ± 50 °C**, **secondary chamber 1050 ± 50 °C**, residence time ≥ 2 s.
- The BMW Rules were amended in 2018 and 2019.
- **E-Waste (Management) Rules, 2022** (in force from **1 April 2023**) replaced the 2016 Rules. They are based on **Extended Producer Responsibility (EPR)** with tradable EPR certificates, cover 106 EEE items including solar PV modules, and route registration through the CPCB portal.
- **Plastic Waste Management Rules, 2016** (amended 2021–24):
  - Carry-bag thickness ≥ **75 µm** from 30 Sept 2021 and ≥ **120 µm** from 31 Dec 2022.
  - Ban on identified **single-use plastic items from 1 July 2022**.
  - EPR for plastic packaging.
  - Non-recyclable plastic is used in road construction (IRC SP 98) and co-processing.
- **Construction & Demolition Waste Management Rules, 2016** (notified 29 March 2016):
  - The generator is responsible for collecting, segregating and storing C&D waste.
  - **Large generators** (≥ **20 tonnes per day** or **300 tonnes per project per month**) must submit a waste management plan and pay charges.
  - Segregation into **five streams**: concrete, soil, steel, wood & plastics, bricks & mortar.
  - Local bodies set up recycling plants. Use of **recycled aggregates** is encouraged, and **IS 383:2016** permits recycled concrete aggregate in concrete.
- **Swachh Bharat Mission**, launched **2 October 2014**:
  - **SBM-Urban 2.0** (launched 1 Oct 2021, to 2026) aims for "Garbage-Free Cities", 100% source segregation, scientific processing and **legacy dumpsite remediation**.
  - **SBM-Gramin Phase II** covers **ODF Plus** villages.
  - The **Swachh Survekshan** annual cleanliness survey has ranked **Indore** top repeatedly since 2017.

MEMORY TRICK

BMW colours: "**Y**ellow = **Y**ou burn it (incinerate)", "**R**ed = **R**ecycle (after autoclave)", "**W**hite = **W**ounding sharps", "**B**lue = **B**roken glass". Landfill siting "1-2-20": **100 m** river, **200 m** pond/highway/habitation, **20 km** airport.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Optimum C/N ratio for composting? → **25–30**.
- Colour of bag for syringes without needles, tubing and catheters (BMW 2016)? → **Red**.
- Typical methane content of landfill gas? → **≈ 50–60%**.
- Waste is segregated at source into how many streams under SWM Rules 2016? → **Three** (wet, dry, domestic hazardous). Under SWM Rules 2026? → **Four** (wet, dry, sanitary, special care).
- Thermal process in the absence of oxygen? → **Pyrolysis**.
- Permeability of the clay liner in a sanitary landfill? → ≤ 10^{-7} **cm/s**.

9.9 Noise Pollution ★★☆

- **Noise** = unwanted sound. The audible range is **20 Hz–20 kHz**; below 20 Hz is infrasound and above 20 kHz is ultrasound. The ear is most sensitive at about **2–5 kHz**. Speed of sound in air ≈ 343 m/s at 20 °C.
- **Decibel (dB)**: a logarithmic ratio scale. The threshold of hearing is **0 dB**; the threshold of pain is about **120–140 dB**.
- **Weighting networks**: **A-weighting** approximates the human ear (it attenuates low frequencies) and is used for environmental and occupational noise, written **dB(A)**. C-weighting is nearly flat (high levels, peak). B is rarely used, and D is for aircraft.
- Noise is measured with a **sound level meter** (fast/slow response) or a noise dosimeter. Hearing is tested with an **audiometer**.

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KEY FORMULAE – DECIBELS

- Sound intensity level: $\mathbf{L_I = 10 \log_{10}(I/I_0)}$, $I_0 = \mathbf{10^{-12}\ W/m^2}$
- Sound pressure level: $\mathbf{L_p = 20 \log_{10}(P/P_0)}$, $P_0 = \mathbf{20\ \mu Pa}$ (2×10^{-5} N/m²); intensity $\propto P^2$
- Sound power level: $L_W = 10 \log(W/W_0)$, $W_0 = 10^{-12}$ W
- Addition: $\mathbf{L_{total} = 10 \log \Sigma\ 10^{L_i/10}}$. Two equal sources → **+3 dB**; 10 equal sources → +10 dB; doubling intensity → +3 dB; doubling pressure → +6 dB
- Quick addition by difference between two levels: 0–1 dB → add 3; 2–3 → add 2; 4–9 → add 1; ≥ 10 → add 0
- Distance (free field): **point source −6 dB per doubling of distance** (inverse square: $L_2 = L_1 - 20 \log(r_2/r_1)$); **line source** (traffic stream) **−3 dB per doubling**
- $\mathbf{L_{eq}} = 10 \log[(1/T)\ \Sigma\ t_i\ 10^{L_i/10}]$ = steady level with the same energy as the fluctuating noise
- $\mathbf{L_{dn}}$ (day–night level) adds a **10 dB penalty to night-time** levels. With the Indian day of 16 h (6 am–10 pm) and night of 8 h: $L_{dn} = 10 \log[(1/24)(16 \times 10^{L_d/10} + 8 \times 10^{(L_n+10)/10})]$
- Traffic noise index: $TNI = 4(L_{10} - L_{90}) + L_{90} - 30$. Noise pollution level: $L_{NP} = L_{eq} + (L_{10} - L_{90})$

- **Statistical levels**: $\mathbf{L_{10}}$ = level exceeded **10%** of the time (peak/intrusive noise, used for traffic). $\mathbf{L_{50}}$ = median. $\mathbf{L_{90}}$ = level exceeded 90% of the time (**background / residual noise**). Always $L_{10} \geq L_{50} \geq L_{90}$.
- **Effects of noise**: annoyance, sleep disturbance, speech interference, raised BP and stress, reduced work efficiency.
- **Temporary threshold shift (TTS)** is recoverable after rest. Repeated exposure causes a **permanent threshold shift (PTS)** = **noise-induced hearing loss (NIHL)**, which is sensorineural (hair cells of the cochlea) and shows a characteristic **dip at 4 kHz**. Other effects: tinnitus and acoustic trauma (from impulse noise).

Noise Pollution (Regulation & Control) Rules, 2000 – Ambient standards, L_{eq} dB(A)	Day time (6 am – 10 pm)	Night time (10 pm – 6 am)
Industrial area	75	70
Commercial area	65	55
Residential area	55	45
Silence zone	50	40

- The Rules were made under the **Environment (Protection) Act, 1986**.
- **Silence zone** = an area of not less than **100 m around hospitals, educational institutions, courts** and religious places, as declared by the competent authority.
- **Loudspeakers / public address systems** are not to be used at night (10 pm–6 am) except in closed premises. The State Government may relax this up to **midnight** for cultural or religious occasions on at most **15 days a year**.
- At the boundary of a public place, a loudspeaker must not exceed ambient + **10 dB(A)** or **75 dB(A)**, whichever is lower.
- **Other limits**: DG sets up to 1000 kVA must not exceed **75 dB(A) at 1 m** from the enclosure surface. Firecrackers are limited to **125 dB(AI)** (or 145 dB(C)pk) at 4 m.
- **Occupational exposure** (Factories Act / Model Rules, following ACGIH/OSHA practice): **90 dB(A) for 8 h/day**. The permissible time halves for every **5 dB** increase: 95 dB(A) for 4 h, 100 dB(A) for 2 h, 105 dB(A) for 1 h. No exposure above **115 dB(A)** (continuous) or **140 dB** peak (impulse).

Noise control at	Measures
Source (most effective)	Quieter design, maintenance and lubrication, **silencers / mufflers**, vibration isolation (springs, rubber pads), enclosures, reducing speed, banning pressure horns
Path (transmission)	Increased distance, **noise barriers** (walls, earth berms; effective only if they break line-of-sight), **green belts** (dense tree belts), absorbent materials, acoustic insulation, land-use zoning, double glazing
Receiver (last resort)	Personal protective equipment: **ear plugs** (≈ 15–30 dB attenuation) and **ear muffs** (≈ 20–40 dB); limiting exposure time by job rotation; sound-proof cabins

MEMORY TRICK

Noise standards, day–night, from the silence zone up: "**50-40, 55-45, 65-55, 75-70**" (night is 10 dB lower, except industrial: 5 dB lower) (Silence, Residential, Commercial, Industrial). Distance rule: "**Point 6, Line 3**" (dB drop per doubling of distance).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Two machines each producing 80 dB operate together; the resultant level is? → **83 dB**.
- Night-time limit for a residential area? → **45 dB(A)** (day 55).
- Silence zone extends around hospitals and schools for at least? → **100 m**.
- Reference sound pressure for 0 dB? → **20 µPa**.
- L_{90} represents? → **Background noise level**.
- Permissible occupational exposure for 8 h? → **90 dB(A)**.

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10. Transportation Engineering

> **NOTE**
>
> Transportation usually gives **6–9 of the 60 MCQs**. Most questions are on road plans and committees, SSD/OSD and superelevation numbers, gradients, CBR and bitumen tests, IRC 37/IRC 58 pavement design, Greenshields and Webster formulae, sign shapes and railway gauges and cant. Learn the **numbers in bold**. Also learn which IRC code covers what. CWC runs ICDs, CFSs and warehouses, so pavements for yards and roads, plus rail and road access, are part of its daily work.

10.1 Highway Development & Planning in India ★★★

- Early road builders: **Tresaguet** (France, 1764), **Telford** and **McAdam**. McAdam used broken stone on a cambered subgrade without a heavy foundation, which led to **WBM**.
- **Jayakar Committee** (Indian Road Development Committee) was appointed in **1927** and reported in 1928. It held that road development was a **national interest**. It recommended an extra tax on petrol, a semi-official technical body and a research organisation.
- **Central Road Fund (CRF)** was set up in **1929** from the petrol cess. **20%** was retained by the Centre for research and special works and **80%** went to the states. It got statutory backing in the **CRF Act 2000** and is now the Central Road & Infrastructure Fund (2018).
- **Indian Roads Congress (IRC)** was formed in **1934** as a semi-official technical body. It frames road codes and standards. The **Motor Vehicles Act** came in 1939 and was replaced in 1988.
- **CRRI** (Central Road Research Institute, New Delhi, a CSIR laboratory) was set up in **1952** for road research. It brought out **Indo-HCM (2017)**.
- **National Highways Act 1956** lets the Centre declare a road as an NH. **NHAI Act 1988** created NHAI, which became operational in **Feb 1995**.

Road plan	Period	Target density	Key features
Nagpur Plan (1st 20-year plan, Nagpur conference 1943)	1943–63 (target achieved early, ≈1961)	**16 km / 100 km²**	**Star & grid pattern**; 5-fold classification NH, SH, MDR, ODR, VR; formula-based lengths
Bombay Plan (2nd)	**1961–81**	**32 km / 100 km²**	≈10.6 lakh km total; **1600 km expressways** (first plan to propose them); more attention to rural roads
Lucknow Plan (3rd)	**1981–2001**	**82 km / 100 km²**	≈27 lakh km; **2000 km expressways**; NH grid so that no part of the country is **>50 km** from an NH; villages with population ≥500 on all-weather roads; energy, environment and safety included
Road Development Plan **Vision 2021**	2001–2021	–	Prepared by MoRTH and IRC; 4-laning of the NH network, expressways

- **Nagpur Plan formula** for NH + SH + MDR length (km) = **(A/8 + B/32 + 1.6N + 8T) − D**. Here A = agricultural area, B = non-agricultural area (km²), N = number of towns and villages with population 2001–5000, T = towns with population >5000 and D = railway route length (km).
- **Saturation system** (maximum-utility-per-unit-length method) is used to choose the best road network from alternatives.
  - Population units: <500 = **0.25**; 501–1000 = **0.5**; 1001–2000 = **1**; 2001–5000 = **2**; >5000 = **4**.
  - Productivity: 1000 tonnes of produce = 1 unit.
  - The network with the **highest utility per km** is chosen.

Classification (Nagpur Plan)	Function / authority
National Highways (NH)	Main arterial roads joining state capitals, ports and foreign highways; Centre (MoRTH / NHAI / NHIDCL)
State Highways (SH)	Arterial roads of a state joining district HQs; State PWD
Major District Roads (MDR)	Serve production areas; join district HQs and taluka HQs to SH/NH
Other District Roads (ODR)	Serve rural areas; join to MDR, markets and taluka HQs
Village Roads (VR)	Join villages to each other and to the nearest higher road
Expressways	Fully **access-controlled**, divided, high-speed (design speed **120 km/h**, IRC SP 99:2013)

- The Lucknow Plan regrouped roads into a three-tier system:
  - **Primary**: expressways and NH.
  - **Secondary**: SH and MDR.
  - **Tertiary**: ODR and VR (rural roads).
- **Urban roads** (IRC 86): **arterial**, sub-arterial, collector streets and local streets.
- **Network facts** (approximate): India has the **2nd largest road network** in the world, after the USA, at **≈66–67 lakh km**.
  - NHs are ≈1.4–1.5 lakh km, only **≈2%** of the length, but carry **≈40%** of road traffic.

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- Roads carry about 60–65% of freight and about 85–90% of passenger traffic.

- **NH numbering** (rationalised 2010): **east–west NHs carry even numbers** and **north–south NHs carry odd numbers**. **NH-44** (Srinagar–Kanyakumari, ≈4,100 km) is the longest.
- **NHDP** (1998 onwards) phase I built the **Golden Quadrilateral** (≈5,846 km). It links **Delhi–Mumbai–Chennai–Kolkata** with 4/6 lanes.
  - **North–South corridor**: Srinagar–Kanyakumari.
  - **East–West corridor**: Silchar–Porbandar.
  - NS + EW together ≈7,300 km.
- **PMGSY** was launched on **25 Dec 2000** to give all-weather roads to unconnected habitations. The thresholds are population **≥500 in plains** and **≥250** in hill, desert and tribal areas. Its design manual is IRC SP 20 (rural roads).
- **Bharatmala Pariyojana** was approved in **2017**. Phase I is ≈34,800 km and covers economic corridors, inter-corridors, feeder routes, border and coastal roads, expressways and **Multimodal Logistics Parks (MMLPs)**.
- **Sagarmala** (2015) is for port-led development. **PM Gati Shakti** National Master Plan came in **Oct 2021** and the National Logistics Policy in **Sep 2022**.
- **Requirements of an ideal alignment**: **short, easy, safe and economical**.
- **Controls on alignment**: **obligatory points** (to pass through, e.g. a bridge site; to avoid, e.g. religious places, marshes), traffic, geometrics, economy and drainage.
- **Engineering surveys, in order**: (1) **Map study** (toposheets) → (2) **Reconnaissance** (Abney level, tangent clinometer, barometer, aerial photographs) → (3) **Preliminary survey** (alternative alignments, quantities, costs) → (4) **Final location & detailed survey** (centre line pegged, L-section and cross-sections).

MEMORY TRICK

"16 – 32 – 82" = Nagpur – Bombay – Lucknow road density (km/100 km²). Remember the order **N-B-L** as **"New Born Lion"**. The years are **1943 – 1961 – 1981**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Which plan recommended the star & grid pattern? → **Nagpur Plan (1943)**.
- Road density target of the Lucknow Plan? → **82 km per 100 km²**.
- Indian Roads Congress was formed in? → **1934**.
- Which committee recommended the Central Road Fund? → **Jayakar Committee (1927)**.
- First road plan to propose expressways? → **Bombay Plan (1600 km)**.
- Saturation system is used for? → **Choosing the optimal road network (max utility per unit length)**.

10.2 Geometric Design – Cross Section & Sight Distance ★★★

- **PCU (Passenger Car Unit)** converts mixed traffic into equivalent cars. The car is taken as **1.0**. For rural roads use **IRC 64:1990** (capacity of rural roads). For urban roads use **IRC 106:1990**, where the PCU values depend on the traffic composition.

Vehicle (IRC 64:1990, rural)	PCU	Vehicle	PCU
Passenger car, pick-up van, auto-rickshaw	**1.0**	Cycle rickshaw	**2.0**
Motor cycle / scooter; pedal cycle	**0.5**	Hand cart	3.0
Light commercial vehicle (LCV)	1.5	Horse-drawn vehicle	4.0
Truck or bus	**3.0**	Bullock cart	**8.0**
Agricultural tractor-trailer	**4.5**	–	–

- Urban values under IRC 106 are lower. For example, a bus or truck is **2.2** when it is 5% of traffic and 3.7 when it is 10% or more. A two-wheeler is 0.5 or 0.75 on the same basis.
- **Design service volume** of a two-lane rural road (IRC 64) in plain terrain is ≈**15,000 PCU/day** (LOS B), depending on curvature.
- **Camber (cross slope)** is the transverse slope that drains surface water. It is given as **1 in n** or %. Steeper camber suits more **pervious** surfaces and heavier rainfall.
- Camber **shapes**:
  - **Parabolic** (elliptical): preferred by fast vehicles.
  - **Straight line**: for rigid (cement concrete) pavements.
  - **Combination**: parabolic at the crown with straight sides.
- Camber is laid with a **camber board** or template.

Surface type (IRC 73)	Heavy rainfall	Light rainfall
Cement concrete / high-type bituminous	**2.0%** (1 in 50)	**1.7%** (1 in 60)
Thin bituminous surface	2.5%	2.0%
WBM and gravel	**3.0%** (1 in 33)	2.5% (1 in 40)
Earth	**4.0%** (1 in 25)	3.0% (1 in 33)

- **Earthen shoulders** are given a cross slope at least **0.5% steeper** than the carriageway.

Carriageway (IRC)	Width
Single lane	**3.75 m**
Two lanes, without raised kerbs	**7.0 m**
Two lanes, with raised kerbs	7.5 m

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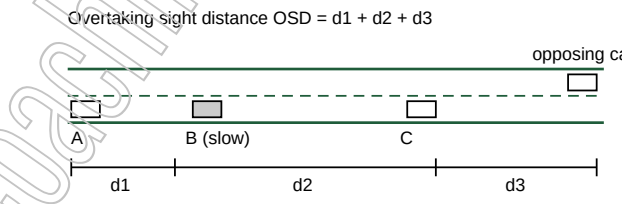
Intermediate carriageway	5.5 m
Multi-lane pavements	**3.5 m per lane**

- **Maximum width of a vehicle** is **2.5 m** under IRC 3 (older texts give 2.44 m). The maximum length of a single-unit truck is **11 m**.
- **Shoulder** minimum width is **2.5 m** (IRC). It serves as an emergency lane and gives lateral support to the pavement.
- **Kerbs**:
  - **Low or mountable** (≈10 cm): used at medians and channelisers; vehicles can climb them.
  - **Semi-barrier** (≈15 cm): along the pavement edge, for heavy pedestrian areas.
  - **Barrier** (≈20 cm): in built-up areas and on bridges.
  - **Submerged**: at pavement level, giving lateral confinement on rural roads.
- **Median** (traffic separator) on rural highways: desirable minimum **5 m**, reducible to 3 m where land is restricted. Medians reduce head-on collisions and night glare.
- **Formation (roadway) width** = carriageway + shoulders.
  - NH/SH in plain terrain: **12 m** (single or two-lane).
  - MDR: 9 m. ODR and VR: 7.5 m.
  - NH/SH in hills: **6.25 m** (single lane) or 8.8 m (two-lane).
- **Right of way (land width)** is the width acquired for the road. For NH/SH in open plain areas it is normally **45 m** (range 30–60 m).
- **Building line** is the line beyond which buildings may be built. **Control line** is the line beyond which the nature of buildings is controlled. For NH/SH in open areas the overall widths are building line **80 m** and control line **150 m**. For MDR they are 50 m and 100 m.
- **Sight distance** is the length of road visible to the driver. IRC heights for SSD are driver's eye **1.2 m** and object **0.15 m**. For OSD and ISD the object height is **1.2 m**.
- **Total reaction time (PIEV)** = **2.5 s** (IRC). PIEV stands for Perception, Intellection, Emotion, Volition.
- **Longitudinal friction coefficient f** = **0.40** at 20–30 km/h falling to **0.35** at 80–100 km/h (IRC). The **lateral** friction coefficient is **0.15**.
- **Stopping sight distance (SSD)** = lag distance + braking distance. It is the **minimum** sight distance that must be available at every point of the road.
- **On single-lane two-way roads**, SSD = **2 × SSD**.
- **Intermediate sight distance (ISD)** = **2 × SSD**. It is provided where OSD cannot be provided.
- **Headlight sight distance** = SSD. It governs valley curves at night.

KEY FORMULAE

- SSD = $\mathbf{v\,t + v^2/(2\,g\,f)}$ (v in m/s) = $\mathbf{0.278\,V\,t + V^2/(254\,f)}$ (V in km/h)
- On a gradient of n%: braking distance = $V^2/[254\,(f \pm 0.01\,n)]$, with + for ascending and − for descending
- With braking efficiency η: braking distance = $v^2/(2\,g\,f\,\eta)$
- OSD (two-way road) = $\mathbf{d_1 + d_2 + d_3}$, where:
  - $d_1 = 0.278\,V_b\,t$, with t = **2 s**
  - $d_2 = 0.278\,V_b\,T + 2s$
  - $d_3 = 0.278\,V\,T$
- Spacing between vehicles s = $\mathbf{0.2\,V_b + 6}$ (m)
- Overtaking time T = √(4s/a) (a in m/s²) = √(14.4 s / A) (A in km/h/s)
- Overtaken vehicle speed V_b = V − 16 km/h (i.e. 4.5 m/s less) if not given
- On a **divided road / one-way**: OSD = $d_1 + d_2$ (no d_3)
- Overtaking zone length: minimum **3 × OSD**, desirable **5 × OSD**



OSD elements: d1 is covered during the 2 s reaction time, d2 during the overtaking time T, and d3 is the distance the opposing car travels in time T.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Total reaction time adopted by IRC for SSD? → **2.5 s**.
- Camber for a WBM road in heavy rainfall? → **3% (1 in 33)**.
- Width of a two-lane carriageway without raised kerbs? → **7.0 m**.
- Intermediate sight distance equals? → **Twice the SSD**.
- Minimum length of an overtaking zone? → **3 × OSD** (desirable 5 × OSD).
- PCU of a bullock cart on rural roads (IRC 64)? → **8**.

10.3 Geometric Design – Horizontal & Vertical Alignment ★★★

Terrain	Cross slope	NH/SH design speed (ruling / min), km/h	MDR	ODR	VR
Plain	**0–10%**	**100 / 80**	80 / 65	65 / 50	50 / 40
Rolling	**10–25%**	**80 / 65**	65 / 50	50 / 40	40 / 35
Mountainous	**25–60%**	**50 / 40**	40 / 30	30 / 25	25 / 20
Steep	**>60%**	**40 / 30**	30 / 20	25 / 20	25 / 20

- **Centrifugal ratio (impact factor)** = P/W = $\mathbf{v^2/(gR)}$.

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- **Overturning** occurs if $v^2/gR > b/2h$, where b is the wheel track and h the height of the C.G.
- **Lateral skidding** occurs if $v^2/gR > f$.
- Skidding happens before overturning when **$f < b/2h$**, which is the usual case and safer.

- **Superelevation (cant / banking)** is the outer edge raised relative to the inner edge.
  - Design rule: superelevation is designed for **75% of the design speed** with f neglected, so the slow-moving mixed traffic of India does not slide inward.
  - Maximum e (IRC): **7%** for plain and rolling terrain and snow-bound hill roads; **10%** for hill roads not bound by snow; **4%** for urban roads with frequent intersections.
  - **Minimum e = camber** (provided where the computed e is less than camber).
- **Design steps** (IRC):
  - Compute $e = (0.75V)^2/(127R) = \mathbf{V^2/(225R)}$.
  - If $e \le 0.07$, provide it.
  - If $e > 0.07$, provide $e = 0.07$ and check $f = V^2/(127R) - 0.07 \le 0.15$.
  - If $f > 0.15$, restrict the speed to $V_a = \sqrt{[127\ R\ (0.07 + 0.15)]} = \sqrt{(27.94\ R)}$ km/h.
- **Attaining superelevation** is done in two steps.
  - Step 1 is **elimination of the crown**. Either the outer half of the camber is rotated about the crown, or the crown is shifted (diagonal crown method).
  - Step 2 is **rotating the pavement** about the **centre line** or about the **inner edge**. Rotation about the centre line balances earthwork, but the inner edge drops. Rotation about the inner edge is better for drainage but needs more earthwork.
  - The rate of change of superelevation (N) is **1 in 150** in plain and rolling terrain and **1 in 60** in hills.

KEY FORMULAE – HORIZONTAL CURVES

- **$e + f = V^2/(127\ R)$** (V km/h, R m) = $v^2/(gR)$
- Ruling minimum radius $R_{ruling} = V^2/[127\ (e + f)]$ with V = ruling design speed. The absolute minimum radius uses the minimum design speed. ($e + f = 0.07 + 0.15 = 0.22$ in plains.)
- **Extra widening** $W_e = W_m + W_{ps}$:
  - Mechanical widening $W_m = \mathbf{n\ l^2/(2R)}$, where n is the number of lanes and l the wheel base (≈6.1 m)
  - Psychological widening $W_{ps} = \mathbf{V/(9.5\ \sqrt{R})}$
- **Transition length** L is the greatest of the following:
  - (i) By rate of change of centrifugal acceleration: $L = \mathbf{v^3/(C\ R)} = 0.0215\ V^3/(C\ R)$, where $\mathbf{C = 80/(75 + V)}$ m/s³ and $\mathbf{0.5 \le C \le 0.8}$
  - (ii) By rate of introducing superelevation: $L = e\ N\ (W + W_e)$ for rotation about the inner edge, or $e\ N\ (W + W_e)/2$ for rotation about the centre
  - (iii) IRC empirical: plain/rolling $L = \mathbf{2.7\ V^2/R}$; mountainous/steep $L = \mathbf{V^2/R}$
- **Shift** $S = \mathbf{L^2/(24\ R)}$
- **Set-back distance** ($L_c > SD$): $m = R - (R - d)\cos(\theta/2)$, where $\theta/2 = S/[2(R - d)]$ radians and d = distance of the centre line of the inner lane from the inner edge. Approximately $m \approx S^2/(8R)$.

Extra widening (IRC), two-lane	Radius (m)	Widening (m)
Two-lane pavement	up to 40	**1.5**
	41–60	1.2
	61–100	0.9
	101–300	0.6
	>300	**Nil**

- For a **single-lane** road the widening is 0.9 m for R ≤ 20 m, 0.6 m for R = 21–60 m and nil beyond.
- **Off-tracking**: the rear wheels follow a path of smaller radius than the front wheels. This is the cause of mechanical widening.
- **Transition curve**: the **ideal shape is the spiral (clothoid)**, where **L × R = constant** and radius ∝ 1/length. It satisfies the condition of a uniform rate of change of centrifugal acceleration. IRC recommends the spiral.
  - The lemniscate is used on roads where the deflection angle is large.
  - The cubic parabola is used on railways.
- **Horizontal curve codes**: IRC 38:1988 (horizontal curves) and IRC SP 23:1983 (vertical curves).

Terrain (IRC)	Ruling gradient	Limiting gradient	Exceptional gradient
Plain & rolling	**3.3% (1 in 30)**	**5% (1 in 20)**	**6.7% (1 in 15)**

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Mountainous & steep, up to 3000 m above MSL	**5% (1 in 20)**	6% (1 in 16.7)	7% (1 in 14.3)
Steep terrain >3000 m above MSL	6% (1 in 16.7)	7% (1 in 14.3)	8% (1 in 12.5)

- **Ruling gradient** is the design gradient, used in normal cases.
- **Limiting gradient** is used where the ruling gradient would cost too much. It is limited to short lengths.
- **Exceptional gradient** is used in unavoidable situations only, for lengths up to about 100 m in a stretch.
- **Minimum gradient** is for drainage of side drains:
  - **1 in 500 (0.2%)** for concrete drains.
  - 1 in 200 (0.5%) for open soil drains.
  - 1 in 100 (1%) for kutcha drains.
- **Grade compensation** on horizontal curves reduces the gradient to offset extra tractive resistance.
  - Compensation = **(30 + R)/R %**, subject to a maximum of **75/R %**.
  - It is **not needed for gradients flatter than 4%**, because the compensated gradient need not be below 4%.
- **Hair-pin bends** (hill roads, IRC 52): minimum inner radius ≈**14 m**; maximum gradient **2.5% (1 in 40)** and minimum 0.5%.
- **Vertical curves** are generally a **square parabola**. It gives a constant rate of change of grade and is easy to set out.
  - **Summit (crest) curve**: designed for **SSD/OSD**. Centrifugal force acts upward and is not critical. A circular curve is ideal, but a parabola is used.
  - **Valley (sag) curve**: designed for **headlight sight distance** (night) and **comfort**. Centrifugal force adds to weight and is critical. A **cubic parabola** transition is preferred.
- **Deviation angle N** = algebraic difference of grades ($n_1 - n_2$). Take it as positive for a summit.

KEY FORMULAE – VERTICAL CURVES

- Summit, SSD (h_1 = 1.2 m, h_2 = 0.15 m): if L > S, L = **N S²/4.4**; if L < S, L = 2S − 4.4/N
- Summit, OSD/ISD ($h_1 = h_2$ = 1.2 m): if L > S, L = **N S²/9.6**; if L < S, L = 2S − 9.6/N
- Valley, comfort: $L = 2\sqrt{(N v^3/C)}$, with C = 0.6 m/s³. Total L = 0.38 $(N V^3)^{1/2}$ (V in km/h)
- Valley, headlight (h = 0.75 m, beam 1°): if L > S, L = **N S²/(1.5 + 0.035 S)**; if L < S, L = 2S − (1.5 + 0.035 S)/N
- Parabola equation: $y = a x^2$, where a = N/(2L)

MEMORY TRICK

"7–10–4" = maximum superelevation for plains, non-snow hills and urban roads. **"0.75 V and 0.15 f"** are the two design numbers for superelevation. For gradients in plains, remember **"30-20-15"** as **1 in 30, 1 in 20, 1 in 15** (ruling, limiting, exceptional).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Superelevation is designed for what percentage of the design speed? → **75%**.
- Ideal transition curve? → **Spiral (clothoid)**.
- Shift of a transition curve? → **L²/24R**.
- Psychological widening? → **V/(9.5√R)**.
- Ruling gradient in plain terrain (IRC)? → **1 in 30 (3.3%)**.
- Grade compensation is not needed for gradients flatter than? → **4%**.

10.4 Highway Materials & Tests ★★★

- **CBR test** (California Bearing Ratio, IS 2720 Part 16) is an **empirical** strength test for subgrade and granular layers. It was developed by the California State Highway Department.
  - The plunger is **50 mm** in diameter. Penetration rate is **1.25 mm/min**.
  - A surcharge of 2.5 kg rings is used. The **specimen is soaked for 4 days (96 h)**.
  - Standard loads: **1370 kg at 2.5 mm** penetration and **2055 kg at 5.0 mm** penetration.
- CBR (%) = test load/standard load × 100. The value at **2.5 mm** is normally reported. If the 5.0 mm value is higher, repeat the test. If it is again higher, adopt the 5.0 mm value.
- **Plate bearing test** gives the **modulus of subgrade reaction k** for rigid pavement design.
  - It uses a **75 cm** diameter plate, with stiffening plates of 60, 45, 30 and 22.5 cm.
  - **k = p/0.125** (kg/cm³), where p is the pressure at **1.25 mm** settlement.
  - A seating load of 0.07 kg/cm² is applied first.
  - Correction for a smaller plate: $k_{75} \approx k_{30} \times 30/75$.
  - Soaking correction: $k_s = k \times (p_s/p)$, from consolidation tests.
- Other subgrade tests:
  - Group index (HRB classification): GI = 0.2a + 0.005ac + 0.01bd, ranging from **0 to 20**. A higher GI means a poorer subgrade.
  - Triaxial test.
  - Resilient modulus M_R (repeated load triaxial).

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Aggregate test	Property	Key details	Limit for bituminous surface course (MoRTH)
Los Angeles abrasion	Hardness (abrasion + impact)	Steel balls 46.8 mm dia (6–12 nos.); 30–33 rpm; 500/1000 revolutions; 1.70 mm sieve. **Best test for hardness**.	**≤ 30%** (BC); ≤ 35% (DBM); ≤ 40% (WBM/WMM)
Aggregate impact value	**Toughness**	13.5–14 kg hammer, **380 mm** fall, **15 blows**; 12.5–10 mm aggregate; 2.36 mm sieve	**≤ 24%** (BC); ≤ 27% (DBM); ≤ 30% (WBM)
Crushing value	**Strength** (resistance to crushing)	**40 t load** at 4 t/min; 12.5–10 mm aggregate; 2.36 mm sieve	≤ 30% for surface course; ≤ 45% for base course
Deval attrition	Hardness (older test)	Cylinders inclined at 30°; 10,000 revolutions	–
Shape tests	Flakiness & elongation	**Flaky**: least dimension < **0.6** × mean dimension. **Elongated**: greatest dimension > **1.8** × mean dimension.	Combined FI + EI **≤ 35%**
Angularity number	Shape	0 (rounded) to 11 (angular) = 67 − % solid volume	–
Stripping value	Adhesion with bitumen	IS 6241; coated aggregate in water at 40 °C for 24 h	Retained coating **≥ 95%**
Soundness	Weathering (durability)	5 cycles in Na_2SO_4 / $MgSO_4$ solution	Loss ≤ **12%** (Na_2SO_4); ≤ **18%** ($MgSO_4$)
Water absorption	Porosity	24 h soaking	**≤ 2%**
Polished stone value	Resistance to polishing (skid)	Accelerated polishing machine	≥ 55 (BC)

- Impact value classes:
  - <10%: exceptionally strong.
  - 10–20%: strong.
  - 20–30%: satisfactory for road surfacing.
  - >35%: weak for surfacing.
- The specific gravity of road aggregates is usually **2.5–3.0**.

Bitumen test	Property	Standard conditions
Penetration (IS 1203)	**Consistency / hardness**	**100 g** needle, **5 s**, **25 °C**; unit = 1/10 mm. A higher value means softer bitumen.
Ductility (IS 1208)	Adhesion / elongation (cohesion)	Briquette 10 mm × 10 mm section, **27 °C**, pulled at **50 mm/min**; result in cm
Softening point (IS 1205)	Temperature susceptibility	**Ring & ball**: 3.5 g steel ball (9.5 mm), heated at **5 °C/min** in water (or glycerine above 80 °C)
Flash & fire point (IS 1209)	**Safety** during heating	Pensky-Martens closed cup (or Cleveland open cup). Flash point (vapour flashes) < fire point (sustained burning). VG grades need flash point **≥ 220 °C**.
Viscosity	Fluid property grading basis)	Absolute viscosity at **60 °C** (poise); kinematic at **135 °C** (cSt); tar viscometer / orifice for cutbacks and emulsions
Specific gravity (IS 1202)	Purity / volumetrics	Pycnometer at 27 °C. Bitumen **0.97–1.02**; tar 1.10–1.25.
Float test (IS 1210)	Consistency of semi-solids	For binders too soft for penetration and too hard for viscosity (e.g. tar)
Spot test	**Overheating / cracking** of bitumen	Oliensis spot test
Loss on heating / TFOT	Volatiles; ageing	Thin-film oven test at 163 °C for 5 h
Solubility	Purity	In trichloroethylene, **≥ 99%**
Water content	Foaming	≤ 0.2% by weight

IS 73:2013 (VG grading)	VG-10	VG-20	VG-30	VG-40
Absolute viscosity at 60 °C (poise)	800–1200	1600–2400	**2400–3600**	3200–4800
Penetration at 25 °C (min)	80	60	45	35
Softening point (min, °C)	40	45	47	50
Kinematic viscosity at 135 °C (min, cSt)	250	300	350	400
Ductility after TFOT (min, cm)	75	50	40	25

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Typical use	Spraying, surface dressing, cold areas (≈80/100 pen)	Cold / hilly areas	**Most common for DBM/BC** (≈60/70 pen)	Heavy traffic, hot areas (≈30/40 pen)

- The **VG number ≈ viscosity at 60 °C / 100** poise. VG grading replaced penetration grading in **2006** (IS 73:2006, revised 2013).
- **Cutback bitumen** (IS 217) is bitumen with a volatile diluent:
  - **RC** (rapid curing): uses naphtha/petrol.
  - **MC** (medium curing): uses **kerosene**. It is used for **prime coat**.
  - **SC** (slow curing): uses light oil.
- **Bitumen emulsion** (IS 8887) is bitumen (≈55–65%) dispersed in water with an emulsifier.
  - Grades are **RS** (rapid setting, for **tack coat** and surface dressing), MS (medium setting, for premix with coarse aggregate) and SS (slow setting, for slurry seal and fine aggregate).
  - **Cationic emulsions** work with wet and electronegative (siliceous) aggregates.
  - Emulsions are used in **wet weather** and cold mixes, with no heating needed.
- **Tar** comes from **destructive distillation** of coal or wood; bitumen from **fractional distillation of petroleum**. Tar is **more temperature-susceptible**, heavier (sp. gr. 1.10–1.25) and soluble in toluene, and is hardly used now.
- **Modified binders**: **PMB** (polymer-modified bitumen: SBS, EVA, plastomers) and **CRMB** (crumb-rubber-modified bitumen). They improve resistance to rutting and cracking and raise the softening point. Specifications: IRC SP 53:2010 and IS 15462:2019 (PMB). Waste plastic in bituminous roads is covered by IRC SP 98.
- **Marshall mix design** (ASTM D1559) is the most used method in India (MS-2 of the Asphalt Institute).
  - Specimen size: **101.6 mm dia × 63.5 mm** high.
  - Compaction: **75 blows per face** for heavy traffic (50 for light), with a 4.54 kg hammer falling 457 mm.
  - The specimen is tested at **60 °C** with loading at **50.8 mm/min**.
- **Stability** is the maximum load carried, in kN. **Flow** is the deformation at maximum load, in mm.
- The **Optimum binder content** is the average of the binder contents at maximum stability, maximum bulk density and 4% air voids (median of the air void range).

Marshall requirements (MoRTH, DBM/BC, heavy traffic)	Value
Stability at 60 °C (min)	**9.0 kN**
Flow	**2–4 mm**
Marshall quotient (stability/flow)	2–5 kN/mm
Air voids (V_a)	**3–5%**
Voids filled with bitumen (VFB)	**65–75%**
Voids in mineral aggregate (VMA)	Minimum depends on NMAS (≈12–14%)

KEY FORMULAE – MIX VOLUMETRICS

- $V_a = (G_t - G_m)/G_t \times 100$, where G_t = theoretical maximum specific gravity and G_m = bulk specific gravity of the mix
- $V_b = W_b\, G_m/G_b$; $VMA = V_a + V_b$; **$VFB = V_b/VMA \times 100$**

- **Superpave** came from the US **SHRP** programme (1987–93). It uses a **gyratory compactor** and **Performance Grade** binders, e.g. **PG 64-22** (maximum 64 °C, minimum −22 °C pavement temperature).

CODE UPDATE

Paving bitumen is graded by viscosity (**VG-10/20/30/40**) under **IS 73:2013**, replacing the penetration grades 80/100, 60/70 and 30/40. The current MoRTH specification is the **5th Revision (2013)**. It withdrew SDBC and expects BC/DBM mixes designed by the Marshall method.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Standard load at 2.5 mm penetration in the CBR test? → **1370 kg**.
- Toughness of aggregate is found by? → **Aggregate impact test**.
- Ring & ball apparatus measures? → **Softening point**.
- Temperature for the ductility test? → **27 °C**.
- VG-30 bitumen is graded on viscosity at? → **60 °C**.
- Air voids in a Marshall-designed BC mix? → **3–5%**.

10.5 Pavement Design ★★★

Feature	Flexible pavement	Rigid pavement
Load transfer	**Grain-to-grain**; load spreads through layers like a **truncated cone**	**Slab (beam) action** spreads load over a wide area
Flexural strength	Negligible	Considerable
Design depends mainly on	**Subgrade CBR** and traffic	**Flexural strength of concrete** (subgrade k matters little)
Design method / code	Mechanistic-empirical, multi-layer elastic; **IRC 37:2018**	Westergaard plate theory; **IRC 58:2015**
Temperature stresses	None (deforms)	**Warping & frictional stresses**; needs joints
Initial cost / maintenance	Low / high	High / low
Design life	≈15–20 years (≥20 for expressways)	≈30 years

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- **Components of a flexible pavement**, from top to bottom:
  - **Surface (wearing) course**: BC, SMA, SDBC or premix carpet.
  - **Binder course**: DBM.
  - **Base course**: WMM or WBM, the main load-spreading layer.
  - **Sub-base**: GSB, which also acts as a drainage and filter layer.
  - **Subgrade**: the top 500 mm of compacted soil, compacted to **97% of MDD** (modified Proctor).
- **Standard axle** = single axle with dual wheels, **80 kN (8.16 t)**. Tandem ≈148 kN; tridem ≈224 kN.
  - Under IRC 37:2018 the tyre contact pressure is **0.80 MPa**; IRC 37:2012 used 0.56 MPa.
  - Dual wheel spacing is 310 mm centre to centre.
- **Fourth power law** (from the **AASHO road test**): damage factor = $(W/W_s)^4$. An axle twice the standard load does 16 times the damage.
- **VDF (vehicle damage factor)** = number of standard axles per commercial vehicle. It is found from an **axle load survey**.
- **ESWL (equivalent single wheel load)** is the single wheel load that gives the same stress or deflection as a dual wheel set.
  - By the **Boyd & Foster** method, ESWL = P at depth d/2 and **2P at depth 2S**, with a log–log straight line between them.
  - Here d is the clear gap between the wheels and S is their centre-to-centre spacing.

KEY FORMULAE – FLEXIBLE PAVEMENT (IRC 37:2018)

- Cumulative standard axles N (msa) = $365 \times A \times [(1+r)^n - 1]/r \times D \times F$
  - A = commercial vehicles per day (CVPD) in the year of opening = $P(1+r)^x$
  - r = growth rate (5% if no data)
  - n = design life
  - D = lane distribution factor (LDF)
  - F = VDF
- LDF: single-lane road = **1.0**; two-lane single carriageway = **0.5**; four-lane single carriageway = 0.4; dual two-lane carriageway = 0.75; dual three-lane = 0.6; dual four-lane = 0.45
- Subgrade resilient modulus: $M_R = 10 \times CBR$ (MPa) for CBR ≤ 5%; $M_R = 17.6 \times CBR^{0.64}$ for CBR > 5%

- IRC 37:2018 is a **mechanistic-empirical** method. Layer strains are computed with **IITPAVE**, a linear-elastic multilayer program, and checked against two criteria:
  - **Fatigue cracking**: horizontal **tensile strain at the bottom of the bituminous layer**.
  - **Rutting**: vertical **compressive strain on top of the subgrade**. The rut-depth limit is **20 mm**.
- **Reliability**: **90%** for design traffic ≥ **20 msa** (NH, SH, expressways) and **80%** for other roads.
- IRC 37 applies to design traffic of about **2 msa and above**. Low-volume rural roads are covered by IRC SP 72:2015. A cement-treated base or sub-base adds its own fatigue check.
- Minimum subgrade CBR for roads with traffic above **450 CVPD** is **8%**. The minimum **design period is 20 years** for NH, SH and urban roads, and 15 years for other roads.
- **Rigid pavement (IRC 58:2015)** is based on **Westergaard's analysis**. The slab is treated as a thin elastic plate on a **dense liquid (Winkler) foundation** with modulus k.
  - Design values: E_c = **30,000 MPa**, μ = **0.15**, α = 10×10^{-6}/**°C**.
  - Concrete must be at least **M40**, with flexural strength **≥ 4.5 MPa** at 28 days (90 days may be used).
  - The slab is designed for the **cumulative fatigue damage** of bottom-up and top-down cracking, using the axle load spectrum (Miner's rule, CFD ≤ 1).
- **Critical load positions**: **interior**, **edge** and **corner**.
  - Load stress is highest at the **corner** for a single load on an unsupported corner. In practice the **edge** region is critical for combined load and temperature stresses.
  - Critical combinations: **Summer mid-day** → edge (load + warping − friction). **Mid-night** → corner (load + warping, top tension).
- **Temperature stresses**:
  - (i) **Warping stress** comes from the temperature differential between top and bottom of the slab. By Bradbury, $\sigma_e = C_x E \alpha \Delta t/2$ at the edge.
  - (ii) **Frictional stress** comes from uniform temperature change and slab movement: $\sigma_f = W L f/(2 \times 10^4)$ kg/cm². Here f ≈ **1.5**, W = unit weight (kg/m³) and L = slab length (m).

KEY FORMULAE – RIGID PAVEMENT

- Radius of relative stiffness: $l = [E h^3/(12(1-\mu^2)k)]^{1/4}$
- Equivalent radius of resisting section: $b = \sqrt{(1.6 a^2 + h^2)} - 0.675 h$ when **a < 1.724 h**; otherwise b = a
- Westergaard corner stress: $\sigma_c = (3P/h^2)[1 - (a\sqrt{2}/l)^{0.6}]$
- Interior stress: $\sigma_i = (0.316 P/h^2)[4 \log(l/b) + 1.069]$
- Edge stress: $\sigma_e = (0.572 P/h^2)[4 \log(l/b) + 0.359]$
- Spacing of contraction joints (from friction): $L_c = 2 \times 10^4 S_c/(W f)$

Joint / steel (rigid)	Purpose & key facts

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Contraction joint (transverse)	Controls cracking from shrinkage and temperature fall. Sawn to ≈1/4–1/3 of slab depth. Spacing ≈**4.5 m** (IRC 58 maximum for normal slabs).
Expansion joint (transverse, full depth)	Allows expansion. 20–25 mm gap with filler and sealant. Now provided **only next to structures** such as bridges and culverts.
Longitudinal joint	Needed when the slab is >**4.5 m** wide. Relieves warping stresses along the lane.
Construction joint	At the end of a day's work. Placed at a contraction joint location.
Dowel bars	**Plain round mild steel** bars at **transverse joints**. They give **load transfer** and allow free movement, so one half is greased or debonded. Designed by **Bradbury's** analysis.
Tie bars	**Deformed** bars at **longitudinal joints**. They hold adjacent slabs together and stop them separating. They are **not** load-transfer devices. Designed for friction on the slab width.

- **WBM** (water-bound macadam) is built in layers 75 mm thick (compacted) using coarse aggregate. Its voids are filled with screenings and binding material (PI < 6), then watered and rolled.
- **WMM** (wet-mix macadam) is graded aggregate mixed with water at OMC in a **plant**, then laid by a paver and compacted. It is better than WBM.
- **GSB** (granular sub-base) uses natural sand, gravel or crushed stone. Requirements: CBR ≥ 30%, LL < 25 and PI < 6. It works as a drainage and filter layer.
- **DBM** (dense bituminous macadam) is a dense, hot-mix binder or base course. **BC** (bituminous concrete) is a dense-graded **wearing course**, the highest quality hot mix. **SDBC** (semi-dense BC) has been withdrawn by MoRTH. **SMA** (stone matrix asphalt) is gap-graded and rut resistant.
- **Prime coat** is a low-viscosity binder (**MC cutback** or SS emulsion) sprayed on a **porous granular surface** such as WMM or WBM. It plugs voids and bonds the layers. The rate is ≈0.6–1.5 kg/m² depending on porosity.
- **Tack coat** is a **very light** application (≈0.20–0.30 kg/m²) of **RS emulsion** or hot bitumen. It goes on an **existing bituminous or concrete surface** to bond a new bituminous layer.
- **Surface dressing** is a sprayed binder covered with stone chips, in one or two coats. It seals the surface and gives skid resistance but does not add strength.
- **Seal coat** is a thin impervious coat over an **open-graded premix carpet (PMC, 20 mm)**. Type A is a liquid seal; Type B is a premixed sand-bitumen seal.
- **Interlocking concrete block pavement** (IRC SP 63:2018) suits **container yards, ICDs/CFSs, warehouse aprons** and slow, heavy loads, which makes it relevant to CWC.

MEMORY TRICK

"Dowel = Do the load transfer, Tie = Tie the slabs together." Dowels are **plain** bars at **transverse** joints. Tie bars are **deformed** bars at **longitudinal** joints. For coats: **Prime on porous, Tack on tarred (bituminous)**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Standard axle load used in IRC 37? → **80 kN single axle, dual wheels**.
- Two strains checked in IRC 37:2018? → **Tensile strain at the bottom of the bituminous layer (fatigue) and vertical compressive strain on the subgrade (rutting)**.
- Radius of relative stiffness depends on? → **E, h, μ of the slab and k of the subgrade**.
- Tie bars are provided at? → **Longitudinal joints**.
- Coat applied on a WMM surface before laying DBM? → **Prime coat**.
- Reliability for design traffic ≥ 20 msa? → **90%**.

10.6 Highway Construction, Maintenance & Drainage ★★☆

- **Embankment** (MoRTH):
  - Laid in layers of ≤ 200–250 mm compacted thickness.
  - Compacted to **95% of MDD** (IS 2720 Part 8, heavy compaction). **Subgrade and shoulders** are compacted to **97%**.
  - Fill material MDD: ≥ 15.2 kN/m³ for embankments up to 3 m and ≥ 16.0 kN/m³ above 3 m. Subgrade material needs ≥ 17.5 kN/m³.
  - Expansive soils (high free swell) are avoided or treated.
- **Compaction equipment**:
  - **Smooth-wheeled (static) rollers** (8–12 t): granular bases and bituminous layers.
  - **Sheepsfoot** rollers: **cohesive (clayey) soils**.
  - **Pneumatic-tyred** rollers: mixed soils and bituminous finishing.
  - **Vibratory** rollers and plate compactors: **granular, cohesionless soils**.
  - Rammers: confined areas.
- **Hot-mix construction sequence**: surface preparation → prime/tack coat → plant mixing (≈150–165 °C for VG-30) → transport (covered) → laying by **sensor paver** → **breakdown rolling** (steel wheel) → intermediate rolling (pneumatic) → finish rolling. Rolling proceeds from the **lower edge to the higher edge**, i.e. edge to crown.

Flexible pavement failure	Cause / identification
Alligator (map / fatigue) cracking	Repeated loads; **fatigue** of the bituminous layer; weak base or subgrade. Interconnected cracks like crocodile skin.

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Rutting	Longitudinal depressions in the **wheel paths**. Caused by permanent deformation of the mix or subgrade, heavy loads, high temperature or excess binder.
Shoving / corrugation	Plastic movement of the surface under braking and acceleration. Caused by an unstable mix or poor bond.
Potholes	Bowl-shaped holes. Caused by water ingress, a weak base or too little binder.
Ravelling	Progressive loss of aggregate from the surface. Caused by poor adhesion, ageing or overheated binder.
Bleeding / flushing	Free binder on the surface. Caused by excess bitumen or low air voids, especially in hot weather.
Stripping	Loss of bond between aggregate and binder in the presence of water.
Reflection cracking	Cracks in an overlay that mirror cracks or joints in the layer below.
Longitudinal / edge cracking	Subgrade settlement, poor shoulder support or edge drainage.

Rigid pavement failure	Cause / identification
Scaling	Peeling of the top mortar surface. Caused by over-finishing, freeze-thaw or a poor mix.
Spalling of joints	Breaking of slab edges at joints. Caused by incompressible material in joints or misaligned dowels.
Pumping (mud pumping)	Fine subgrade soil ejected through joints and cracks with water under traffic. Leads to loss of support. Prevented by a granular sub-base and good drainage.
Faulting	Difference in level between slabs across a joint. Caused by poor load transfer (no dowels) or pumping.
Corner cracks / corner break	Corner loading combined with warping, loss of support or no dowels.
Warping cracks; shrinkage cracks	Warping cracks come from inadequate joints and temperature differential. Shrinkage cracks come from poor curing.
Blow-up (buckling)	Expansion that is not relieved, e.g. joints blocked in hot weather.

- **Structural evaluation**:
  - **Benkelman Beam Deflection (BBD)**, IRC 81:1997. The beam uses a 2:1 lever arm. The test truck has an 8170 kg rear axle with 5.6 kg/cm² tyre pressure.
    - Readings are corrected to a standard temperature of **35 °C** and for season (moisture).
    - **Characteristic deflection** = mean + **2σ** for NH/SH and mean + σ for other roads.
  - **Falling Weight Deflectometer (FWD)**, IRC 115:2014. It gives a deflection bowl, from which layer moduli are back-calculated. It is now preferred for overlay design.
- **Functional evaluation**:
  - **Roughness** is measured with a **bump integrator** (mm/km), MERLIN or laser profilometer. It is expressed as **IRI (International Roughness Index, m/km)** (IRC SP 16:2019).
  - Distress surveys (Network Survey Vehicle) and PCI ratings are also used.
- **Overlays**:
  - Flexible on flexible: thickness from BBD or FWD.
  - Rigid on flexible: whitetopping (IRC SP 76).
  - Flexible on rigid: a crack-relief layer is needed against reflection cracking.
- **Maintenance** may be **routine** (patching, crack sealing), **periodic** (renewal coat), special or emergency.
- **Highway drainage objectives**: keep the **subgrade** moisture low, since water is the main enemy of pavement strength, and remove surface water quickly.
- **Surface drainage**:
  - Camber and shoulder slope.
  - **Side drains**: open trapezoidal or lined drains in rural areas, kerb-and-gutter with inlets in urban areas.
  - Catch-water drains on hill slopes.
  - Drainage design is based on runoff by the **rational formula Q = CIA/360** (Q in m³/s, I in mm/h, A in ha).
- **Sub-surface drainage**:
  - **Lowering the water table** with longitudinal and transverse drains. The highest water table should be at least **≈1.0–1.2 m below the subgrade**.
  - Control of seepage and capillary rise. A **capillary cut-off** can be a granular blanket, an impermeable membrane or geotextile.
  - A drainage layer (open-graded GSB) with filter criteria.
- **Cross-drainage works**:
  - **Culvert**: total span **≤ 6 m** (IRC). Types are pipe, box, slab and arch culverts.
  - **Minor bridge**: 6–60 m. **Major bridge**: > 60 m.
  - **Causeway**: a submersible road crossing for low-volume roads.
  - Minimum pipe culvert diameter on highways is typically **1.0 m** (IRC SP 13, for ease of cleaning); the NH EPC manuals (IRC SP 73/84) specify 1.2 m.
- **Hill roads** (IRC 52): **retaining walls** on the valley side, **breast walls** on the hill side, catch-water drains above the road, hair-pin bends and passing places on single-lane roads.
- **Low-volume (rural) roads**: IRC SP 20:2002 (Rural Roads Manual) and IRC SP 72:2015 (flexible pavements for low-

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volume roads), both used for PMGSY. Stabilised soils, local materials and cement concrete or interlocking block in villages are common.

- **Soil stabilisation**: **lime** for clayey soils, **cement** or bitumen for sandy soils, and mechanical stabilisation by proportioning.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Benkelman beam is used to measure? → **Rebound deflection of a flexible pavement** (IRC 81).
- Pumping is a failure of? → **Rigid pavement**.
- Alligator cracking is caused mainly by? → **Fatigue (repeated loading)**.
- Roughness of a road is measured by? → **Bump integrator (IRI)**.
- Sheepsfoot rollers suit? → **Cohesive soils**.
- Maximum span of a culvert (IRC)? → **6 m**.

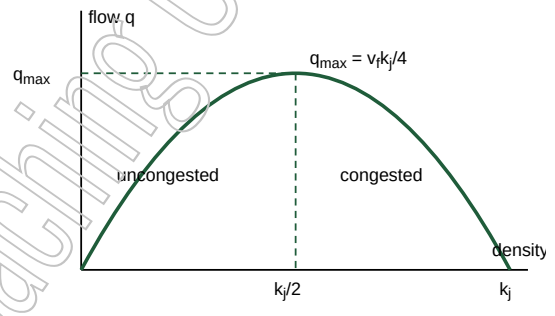
10.7 Traffic Engineering ★★★

- **The 3 Es of traffic engineering**: **Engineering, Enforcement, Education**. Environment and Emergency care are sometimes added.
- **Volume studies**: manual or automatic counts, given as **ADT/AADT**. The **30th highest hourly volume** is the **design hourly volume**.
- **Spot speed** methods: enoscope (mirror box), pressure contact tubes, radar speed meter and photographic methods.
- **Speed and delay (journey) studies**: floating car method, **moving observer method** (Wardrop & Charlesworth), licence plate method, elevated observer and interviews.
- **O-D (origin–destination) surveys**: road-side interview, licence plate method, return postcard, tag-on-car, home interview and work-place interview. Results are shown as **desire lines** (straight lines from origin to destination, thickness ∝ trips). O-D studies are used to plan new roads and bypasses.

Speed term	Use / definition
98th percentile speed	**Geometric design speed**
85th percentile speed	**Safe speed limit** (upper / maximum speed limit)
15th percentile speed	**Minimum speed limit** (on expressways, to stop slow vehicles)
Time-mean speed (v_t)	Arithmetic mean of spot speeds at a point. It is always **≥ space-mean speed**.
Space-mean speed (v_s)	Harmonic mean of spot speeds; length ÷ average travel time. Used in $\mathbf{q = k\,v_s}$.
Running speed vs journey speed	Running speed excludes stopped delays. Journey (overall) speed includes them, so running speed ≥ journey speed.

KEY FORMULAE – TRAFFIC FLOW

- Fundamental relation: $\mathbf{q = k \times v_s}$, with q in veh/h, k in veh/km and v_s in km/h
- $v_t = v_s + \sigma_s^2/v_s$
- Time headway h = 3600/q (s); space headway (spacing) s = 1000/k (m)
- **Greenshields (linear speed–density) model**: $v = v_f(1 - k/k_j)$; $q = v_f\,k - (v_f/k_j)\,k^2$ (a parabola)
- Maximum flow occurs at $\mathbf{k = k_j/2}$ and $\mathbf{v = v_f/2}$, giving $\mathbf{q_{max} = v_f\,k_j/4}$
- **Peak hour factor** PHF = hourly volume/(4 × peak 15-min volume), always ≤ 1
- Theoretical lane capacity C = 1000 V/S (veh/h), where S = spacing in m and V in km/h



Greenshields flow–density curve: a parabola. Flow is zero at k = 0 and at jam density k_j, and is maximum at $k_j/2$. The slope of the curve at the origin is the free-flow speed v_f.

- **Capacity** is the maximum hourly rate at which vehicles can pass a point under prevailing conditions. The older terms are **basic capacity** (ideal conditions) ≥ possible capacity ≥ **practical capacity** (design value).
- **Level of Service (HCM)**: **A** free flow → B → **C** stable flow (usual design LOS) → D → **E** at **capacity** → **F** forced/breakdown flow. India uses Indo-HCM (CSIR-CRRI, 2017).
- **Parking studies**: in–out survey, fixed-period sampling and licence plate method. Measures include parking accumulation, parking volume, **turnover** (vehicles per bay per period) and **parking index** (occupancy %).
- **On-street parking**: **parallel** parking is the **safest** but holds the fewest cars; **90°** parking holds the **most cars per kerb length** but is the most hazardous. Off-street: surface lots, multi-storey and automated parking.
- **Accident studies**:
  - **Collision diagram**: shows the approximate **paths of vehicles and pedestrians** involved in accidents, using symbols.
  - **Condition diagram**: a scaled drawing of the **physical features** of the site (kerbs, signs, buildings, lighting).
  - Accident rate is expressed per 100 million vehicle-km or per 10,000 vehicles.

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Traffic sign (IRC 67:2022)	Shape & colour	Examples
Mandatory / regulatory	**Circular**, red border, white background (prohibitory). Compulsory signs: blue disc.	Speed limit, no entry, no parking, compulsory turn left
STOP	**Octagonal**, red with white letters	At major-road junctions
GIVE WAY	**Inverted (downward-pointing) equilateral triangle**, red border	At minor-road entry
Cautionary / warning	**Equilateral triangle, apex up**, red border, white background	Curve, narrow bridge, school, hump
Informatory	**Rectangular**. Green for NH/SH directions, blue for other roads and facilities.	Direction, place identification, petrol pump, hospital

- **Road markings** (IRC 35:2015):
  - Most lines are **white**. Centre lines and lane lines are **broken white**.
  - **Continuous (solid) lines** mean **no crossing or overtaking**. Double or yellow lines are barrier lines.
  - **Yellow** is used for no-parking kerb markings and for no-overtaking/barrier lines.
  - Other markings include stop lines, **zebra crossings**, arrows, chevrons, hatched areas, and kerb markings in alternate black and white or yellow.
  - Thermoplastic paint and retro-reflective studs (cat's eyes) are used.
- **Traffic signals** (IRC 93:1985):
  - Types: **fixed-time** (pre-timed), **vehicle-actuated** and coordinated or **ATCS** (adaptive).
  - Coordinated systems are simultaneous, alternate, flexible progressive or a **green wave**.
  - Amber (change interval) is ≈2–4 s.
  - Pedestrian walking speed is taken as **1.2 m/s**.
- **Signal design methods**: trial cycle, approximate, **Webster's method** and the IRC method (pedestrian-based).

KEY FORMULAE – SIGNALS & ROTARY

- **Webster's optimum cycle: $C_0 = (1.5\,L + 5)/(1 - Y)$** (s)
  - L = total lost time per cycle = 2n + R, where n = number of phases (≈2 s lost each) and R = all-red time
  - **$Y = \Sigma\, y_i = \Sigma\,(q_i/s_i)$** for the critical approaches; Y must be < 1
- Effective green $g_i = (y_i/Y)(C_0 - L)$
- **Saturation flow** (Webster): s = **525 w** PCU/h for approach width w = 5.5–18 m
- Rotary capacity (Wardrop): $Q_p = 280\, w\, (1 + e/w)(1 - p/3)/(1 + w/l)$
  - w = width of weaving section (6–18 m)
  - e = average entry width
  - l = weaving length
  - p = proportion of weaving traffic = (b + c)/(a + b + c + d)
- Width of weaving section $w = (e_1 + e_2)/2 + 3.5$ m

- **At-grade intersections**:
  - Uncontrolled.
  - **Channelised** (islands guide the movements).
  - Priority (stop or give-way control).
  - Signalised.
  - **Rotary/roundabout** (IRC 65:2017).

A 4-legged uncontrolled intersection has **32 conflict points** (16 crossing, 8 merging and 8 diverging). A rotary converts crossing conflicts into weaving.

Rotary design element (IRC)	Rural	Urban
Design speed	**40 km/h**	**30 km/h**
Entry radius	20–35 m	15–25 m
Exit radius	1.5–2 × entry radius	
Central island radius	≈1.33 × entry radius (slightly larger than the curve at entry)	
Weaving length	45–90 m	30–60 m
Suitable traffic (all approaches)	**≈500–3000 veh/h**. Below this, a rotary is not justified. Above it, use signals or a grade separation.	

- **Grade-separated interchanges**:
  - **Full cloverleaf**: 4 loops; full free movement but large area.
  - **Diamond**: major road crossing a **minor** road.
  - **Trumpet**: **3-leg (T)** junction.
  - Directional and rotary interchanges are also used.
- **ITS**: ATMS, ATIS, variable message signs, adaptive signals, and electronic tolling (**FASTag** RFID, mandatory on NH plazas from **2021**; GNSS/ANPR barrier-free tolling being introduced).

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MEMORY TRICK

Sign shapes: **"Order in a Circle, Warning in a Triangle, Information in a Rectangle."** The two odd ones out are **STOP = 8 sides** and **Give Way = upside-down triangle**. For percentile speeds use **"98 Design, 85 Limit, 15 Minimum."**

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Safe speed limit is fixed at which percentile speed? → **85th**.
- In the Greenshields model, maximum flow occurs at density? → **$k_j/2$**, with $q_{max} = v_f k_j/4$.
- Webster's optimum cycle length? → **(1.5L + 5)/(1 − Y)**.
- Shape of a cautionary sign? → **Equilateral triangle, apex upward**.
- Diagram showing the paths of vehicles in accidents? → **Collision diagram**.
- Interchange for a T-junction? → **Trumpet**.

10.8 Railway, Airport, Bridges & Tunnels ★★☆

Gauge (clear distance between inner faces of rail heads)	Width	Remarks
Broad gauge (BG)	**1676 mm** (5′6″)	Standard for Indian Railways; first train Bombay–Thane, 16 Apr 1853 (34 km)
Standard gauge	**1435 mm**	Most metros (DMRC phases 2+), Mumbai–Ahmedabad high-speed rail
Metre gauge (MG)	**1000 mm**	Being converted to BG
Narrow gauge (NG)	**762 mm** (2′6″) and **610 mm** (2′)	Hill railways, e.g. Darjeeling (610 mm), Kalka–Shimla (762 mm)

- **Project Unigauge** (1992) converts MG and NG to BG.
- **Rails**: **flat-footed (Vignoles)** section; BG main lines use **52 and 60 kg/m** rails; standard length **13 m** (BG) and 12 m (MG); **LWR/CWR** on main lines.
- **Coning of wheels**: wheel treads are coned at **1 in 20**. This keeps the axle centred and reduces wear and slip on curves. Rails are given an inward **tilt of 1 in 20** (adzing of sleepers or canted bearing plates).
- **Creep** is the **longitudinal movement of rails** in the direction of traffic. It is caused by the wave action of moving loads, braking/acceleration and temperature. It is countered by **anti-creepers** and is more on the down-gradient and the outer rail of curves.
- **Wear** is worst on the **outer rail of curves** (side wear). **Hogging** = rail ends bent down at joints.
- **Sleeper density** is written as **M + x**, where M = rail length in metres and x = 3 to 7. For example, BG main lines use M + 7 = 20 sleepers per 13 m rail. Modern PSC track uses ≈1540–1660 sleepers per km (≈60–65 cm spacing).
- **Sleeper types**: wooden (best elasticity, standard BG size 2.74 m × 25 cm × 13 cm), steel trough, cast-iron (CST-9 pot) and **PSC (prestressed concrete) mono-block** sleepers, which are now standard.
- **Ballast**: angular crushed stone, **50 mm** (BG), minimum cushion ≈**250–350 mm**. It transfers load, drains and holds the track.
- **Points & crossings**: a turnout has stock rails, **tongue (switch) rails**, lead rails, **crossing (frog)**, check and wing rails. Crossing number N (1 in 8.5, 1 in 12, 1 in 16): larger N means a flatter angle and higher speed. N is measured by the **right-angle (Cole's)**, centre-line or isosceles method.
- **Gradients**:
  - **Ruling gradient** is the maximum gradient a train of full load can climb with one locomotive. It is ≈**1 in 150 to 1 in 200** in plains and 1 in 100 to 1 in 150 in hills.
  - **Momentum gradient** is steeper than ruling and is climbed using momentum gained on a preceding down-grade.
  - **Pusher (helper) gradient** needs an extra engine, e.g. **1 in 37** on ghat sections.
  - **Station yard gradient**: not steeper than **1 in 400**; desirable 1 in 1000.
- **Grade compensation on curves**: **0.04% per degree** of curve on BG, 0.03% on MG and 0.02% on NG.
- Degree of curve D ≈ **1750/R** (30.5 m chord).

KEY FORMULAE – RAILWAY CURVES

- Equilibrium cant **$e = G V^2/(127 R)$** (e in mm, G = dynamic gauge in mm (1750 for BG), V in km/h, R in m)
- Maximum permissible speed on a transitioned BG curve: $V = 0.27 \sqrt{[(C_a + C_d) R]}$
- Cant deficiency C_d = equilibrium cant for the maximum speed − actual cant. Cant excess = actual cant − equilibrium cant for the slow (booked) speed.
- Length of transition (IR) = greatest of $0.008\, C_a\, V_m$, $0.008\, C_d\, V_m$ and $0.72\, C_a$ (m)
- **Negative cant** occurs on a turn-out that curves opposite to the main-line curve (contrary flexure).

Cant limits (IRPWM)	BG	MG	NG (762)
Maximum cant	**165 mm** (185 mm for nominated high-speed groups)	100 mm	65 mm
Maximum cant deficiency	**75 mm** (100 mm for nominated high-speed routes/stock)	50 mm	40 mm
Maximum cant excess	75 mm	65 mm	–

- **Indian Railways** (approximate): ≈68,000 km route, almost all BG and nearly fully electrified. **Kavach** is the indigenous

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train protection system. The **Chenab bridge** is the world's highest railway arch bridge.

- **Dedicated Freight Corridors** (DFCCIL, 2006):
  - **Eastern DFC**: Ludhiana (Sahnewal)–Sonnagar, ≈1,337 km.
  - **Western DFC**: JNPT (Mumbai)–Dadri, ≈1,506 km. It is designed for **double-stack containers** and 25 t axle loads.
- **MAHSR** (Mumbai–Ahmedabad bullet train): ≈508 km, standard gauge, Japanese **Shinkansen** technology (JICA), 320 km/h, built by NHSRCL.
- **Runway orientation**:
  - The runway is aligned along the **prevailing wind**, found from a **wind rose diagram**.
  - A Type I wind rose shows direction and duration. A Type II wind rose also shows intensity, drawn as concentric circles.
  - Runways should give a **usability (wind coverage) factor ≥ 95%** (ICAO).
  - Take-off and landing are done **into the wind**.
- **Permissible crosswind component (ICAO)**:
  - **37 km/h (20 kt)** for reference field length ≥ 1500 m.
  - **24 km/h (13 kt)** for 1200–1500 m.
  - **19 km/h (10 kt)** for < 1200 m.
- **Runway number** = magnetic bearing ÷ 10, rounded. For example, a runway with bearing 270° is numbered **27** and its opposite end **09**.

KEY FORMULAE – BASIC RUNWAY LENGTH CORRECTIONS (ICAO/FAA)

- **Elevation**: increase the basic length by **7% per 300 m** rise above MSL
- **Temperature**: increase the elevation-corrected length by **1% per 1 °C** by which the aerodrome reference temperature exceeds the standard atmosphere temperature at that elevation. Standard temperature = 15 °C − 0.0065 × elevation (m).
- If elevation + temperature corrections together exceed **35%**, a special study is needed.
- **Gradient** (take-off, FAA): further increase by **20% per 1% of effective gradient**. Effective gradient = (max RL − min RL)/runway length.
- Airport reference temperature ART = $T_a + (T_m - T_a)/3$, where T_a = monthly mean of average daily temperature and T_m = monthly mean of maximum daily temperature, both for the hottest month

ICAO aerodrome reference code	Basis	Classes
Code number 1–4	Aeroplane reference field length	1: < 800 m; 2: 800–1200 m; 3: 1200–1800 m; **4: ≥ 1800 m**
Code letter A–F	Wingspan	A < 15 m; B 15–24; C 24–36; D 36–52; E 52–65; **F 65–80 m** (e.g. A380)

- **Airport components**: runway (with strip, RESA, stopway/clearway), **taxiway** (rapid-exit at ≈30°), **apron** (aircraft loading/parking), holding apron, hangar (repair) and terminal.
- Indian airports are managed mainly by **AAI** (formed 1995). The regulator is the **DGCA**. Air cargo terminals act as part of the logistics chain (CWC has operated air cargo complexes).
- **Bridge components**:
  - **Superstructure**: deck, girders, wearing coat, railings.
  - **Bearings**: elastomeric, POT-PTFE, roller/rocker.
  - **Substructure**: **piers**, **abutments, wing walls**, return walls.
  - **Foundation**: open, pile or **well (caisson)**. Well foundations are typical for large Indian rivers.
- **Types by structure**: slab (≈up to 8–10 m), **T-beam** (≈10–25 m), PSC box girder (30–60 m+), **balanced cantilever**, arch, truss, **cable-stayed** (Vidyasagar Setu, Bandra–Worli Sea Link) and **suspension** (longest spans).
- **Economic span**: the total cost is a minimum when the **cost of the superstructure of one span = cost of the substructure (one pier + foundation)**.
- **Afflux** is the **rise in the water level upstream** of a bridge caused by the constriction of the waterway. Molesworth's formula: $h = (V^2/17.88 + 0.01524)(A^2/a^2 - 1)$ m. Clearance (freeboard) is measured above HFL plus afflux.
- **IRC loading** (IRC 6:2017):
  - **Class 70R**: 70 t tracked vehicle or 100 t wheeled vehicle. Used for bridges on NH/SH and in industrial areas.
  - **Class AA**: 70 t tracked or 40 t wheeled. This is the older heavy loading; 70R is the current heavy loading.
  - **Class A**: the **normal** loading on all permanent bridges. It is a 554 kN train of vehicles.
  - **Class B**: **light loading** for temporary and timber bridges.
- **Impact factor** (IRC 6): for Class A on RCC, about 4.5/(6 + L). It decreases with span.

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KEY FORMULAE – SCOUR (LACEY / IRC 78)

- Lacey's regime waterway (linear) **$W = 4.8\sqrt{Q}$** (m), with Q in m^3/s
- Normal scour depth: d_{sm} = **$1.34\,(q^2/f)^{1/3}$** when the waterway is restricted (q = discharge per metre width). For an unrestricted (regime) channel, d = **$0.473\,(Q/f)^{1/3}$**.
- Lacey silt factor **$f = 1.76\sqrt{d_m}$**, with d_m = mean particle size in mm
- Maximum scour depth for design (IRC 78): **2.0 d_{sm} at piers**; 1.27 d_{sm} at abutments (with approach retained) to 2.0 d_{sm} (scour all round)
- Bends: straight reach 1.27 d, moderate bend 1.5 d, severe bend 1.75 d, right-angled bend 2.0 d

- **Tunnel shapes**: **circular** (best against external and water pressure in **soft ground**; TBM), **horseshoe** (most common in **rock** for roads and railways), **D-shaped** (hard rock), **egg-shaped** (sewers).
- **Soft-ground methods**: **forepoling**, **needle beam**, liner plate, **shield (Greathead)**, compressed air, EPB/slurry **TBM** (metros). **Hard-rock methods**: **full face**, **heading & bench**, **drift**, pilot tunnel, **drill & blast**, TBM.
- **NATM** (New Austrian Tunnelling Method) uses the self-supporting strength of the rock, with **shotcrete + rock bolts** and continuous monitoring.
- **Ventilation**: natural (short tunnels) or mechanical. Road tunnels use **longitudinal** (jet fans), transverse or semi-transverse systems. The **Atal Tunnel** (Rohtang, ≈9 km, 2020) is the longest highway tunnel above 10,000 ft.
- **Docks & harbours**:
  - A **port** is a harbour with terminal facilities. Breakwaters may be rubble-mound or vertical-wall.
  - **Wet dock**: water level held by **lock gates**. **Dry (graving) dock**: for ship repair.
  - **Quay/wharf** lies parallel to the shore; a **jetty/pier** projects into the sea; **fenders** absorb berthing impact.
  - **Littoral drift** is sand moved along the coast by waves.
- **CWC logistics**: a **CFS** (Container Freight Station) is an off-dock facility **near a port**; an **ICD** (dry port) is **inland**, linked by rail or road. Their civil works include heavy-duty **container yard pavements** (rigid or block, IRC SP 63), **railway sidings**, warehouse floors and drainage.

CODE UPDATE

Current versions:

- **IRC 37:2018**: flexible pavements, 4th revision; tyre pressure 0.80 MPa.
- **IRC 58:2015**: rigid pavements.
- **IRC 6:2017**: bridge loads.
- **IRC 67:2022**: road signs.
- **IRC 35:2015**: road markings.
- **IRC 65:2017**: roundabouts.
- **IRC 73**: rural geometric design, revised in 2023 (first issued 1980).
- **IS 73:2013**: VG bitumen.

MEMORY TRICK

Runway corrections: **"7 – 1 – 20"** means **7% per 300 m** elevation, **1% per °C** and **20% per 1% gradient**. Gauges: **"1676 – 1435 – 1000 – 762 – 610"**, read in order as **Big, Standard, Metre, Narrow, Narrower**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Width of broad gauge in India? → **1676 mm**.
- Coning of wheels is provided at? → **1 in 20**.
- Correction to runway length for elevation? → **7% per 300 m**.
- Runway orientation is decided using? → **Wind rose diagram**.
- Economic span of a bridge is reached when? → **Cost of superstructure = cost of substructure**.
- Best tunnel shape for soft ground under water pressure? → **Circular**.

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11. Surveying, GIS & GPS

> **NOTE**
> Surveying gives about 3–6 MCQs in Civil JE/AE/PSU papers. Most are quick numericals: WCB ↔ RB, levelling checks, curvature/refraction, tape corrections, curve elements, tacheometry and closing error. Fact questions cover contours, compass types, theodolite adjustments, GPS and NavIC. Learn the formula boxes and tables by heart.

11.1 Principles & Classification of Surveying ★★★

- **Surveying**: the art of finding the relative positions of points on, above or below the earth's surface by measuring **horizontal distances, vertical distances (elevations) and angles/directions**.
- **Levelling**: the branch that deals with measurements in the **vertical plane**.
- **Plane surveying**: ignores the curvature of the earth. The earth's surface is treated as a plane, so a plumb line is taken to be the same direction everywhere and triangles are plane triangles. Valid for areas **< 250 km²** (some books say 260 km²).
- **Geodetic surveying**: takes the **curvature of the earth** into account. Used for large areas and high precision (national control networks, GTS). Lines are arcs and triangles are **spherical triangles**.
- **Spherical excess**: the angles of a spherical triangle exceed 180° by about **1″ per ≈ 195.5 km²**. Mean earth radius R ≈ **6370 km**.

Fundamental principle	Meaning / purpose
Working from whole to part	First set up a framework of main control points with high precision, then fill in the details. It **localises errors** and stops them accumulating.
Locating a point by at least two independent measurements from reference points	For example, two distances (chain survey), a distance and an angle (traverse/radiation), or two angles (intersection/triangulation).

Basis of classification	Types
Nature of field	Land survey (topographic, cadastral, city), marine/**hydrographic** (water bodies, soundings), astronomical
Object/purpose	Engineering, military, mine, geological, archaeological, **cadastral** (property boundaries), **topographic** (natural and artificial features plus relief), route, control
Instruments	Chain/tape, compass, plane table, theodolite, levelling, tacheometric, EDM/total station, photogrammetric, GPS/GNSS
Method	**Triangulation** (angles) and **traversing** (lengths plus directions); trilateration (lengths only)

Errors

Type	Nature	Behaviour	Examples
Mistakes / gross errors	Carelessness, inexperience	Cannot be treated mathematically. Found by checks.	Wrong booking, missing a chain length, reading 6 for 9
Systematic (cumulative)	Follow a definite law; **same sign** each time	Error grows **∝ n** (number of observations). Can be found and corrected.	Chain too long or short, temperature, sag, staff not vertical
Accidental (compensating, random)	Beyond the observer's control; sign may be + or −	Partly cancel out. Error grows **∝ √n**. Handled by the theory of probability (least squares).	Small errors of reading, centring or bisection

- **Accuracy** = how close a measurement is to the **true value**. **Precision** = how close repeated measurements are to **each other** (degree of refinement). A result can be precise without being accurate when a systematic error is present.
- **Residual (v)** = measured value − **most probable value (MPV)**. MPV of equal-weight observations = **arithmetic mean**; unequal weights → **weighted mean**.
- Weight ∝ number of observations ∝ **1/(probable error)²** ∝ 1/(route length) in levelling.
- **Principle of least squares**: the MPV makes the **sum of squares of the residuals a minimum**.

> **KEY FORMULAE**
> - Probable error of a single observation $E_s = \pm 0.6745\sqrt{[\Sigma v^2/(n-1)]}$
> - Probable error of the mean $E_m = E_s/\sqrt{n}$
> - Relative precision = error ÷ measured length, stated as 1 in N

Survey of India – history facts

- **Survey of India (SoI)**: set up in **1767**, the **oldest scientific department** of GoI. HQ **Dehradun**, under the **Dept of Science & Technology**, headed by the **Surveyor General of India**.
- **Great Trigonometrical Survey (GTS)**: began **1802** under **William Lambton** (first base near Madras). **George Everest** (Surveyor General 1830–43) completed the Great Arc; **Everest spheroid** used for Indian maps. **Radhanath Sikdar** (1852) computed Peak XV as the highest peak.

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- Plane surveying is acceptable up to an area of about? → **250 km²**.
- Principle of "whole to part" is used to? → **Prevent accumulation of errors**.
- Compensating errors are proportional to? → **√n**.
- Error due to wrong length of chain is? → **Cumulative (systematic)**.
- HQ of Survey of India? → **Dehradun** (set up in 1767).
- MPV makes which quantity a minimum? → **Sum of squares of residuals**.

11.2 Maps & Scales ★★★

- **Engineer's scale**: 1 cm = x m. **RF** = map distance ÷ ground distance in the **same units** (1 cm = 10 m → **1/1000**).
- **Graphical scale**: stays correct even if the map **shrinks or is enlarged**.
- Large scale: 1 cm ≤ 10 m; small scale: 1 cm ≥ 100 m. **Smaller denominator = larger scale = more detail**.

Scale type	Reads	Remark
Plain scale	**Two** dimensions (units and tenths, e.g. m and dm)	Simple line divided into units and sub-units
Diagonal scale	**Three** dimensions (e.g. m, dm, cm)	Uses similar triangles. Small divisions are obtained from diagonals.
Vernier scale	Fractions of the smallest main-scale division	LC = s/n = 1 MSD − 1 VSD
Scale of chords	Angles	Used to set out or measure angles on a map

- **Direct vernier**: n VSD = **(n − 1)** MSD, same direction (most common). **Retrograde**: n VSD = **(n + 1)** MSD, opposite direction. Others: double (theodolites), extended.

KEY FORMULAE

- Least count of vernier = s/n (s = value of one main-scale division, n = number of vernier divisions)
- Shrinkage factor (SF) = shrunk length ÷ original length
- Shrunk scale = SF × original scale. True ground distance = measured map distance ÷ shrunk scale
- Wrong scale: correct length = (RF used ÷ correct RF) × measured length. Correct area = (RF used ÷ correct RF)² × measured area

Recommended scales

Purpose	Scale
Building sites	1 cm = 10 m or less (**1:1000** or larger)
Town planning, reservoirs	1 cm = 50–100 m
Cadastral (village) maps	Large scale, typically **16″ = 1 mile (≈ 1:3960)**
Longitudinal section	Vertical scale exaggerated ≈ 10× (H 1 cm = 10–200 m; V 1 cm = 1–2 m)
Cross-section	Same scale both ways
Topographic / geographical	1:25,000 – 1:250,000 / 1:1,000,000 and smaller

Survey of India toposheets

Scale	Extent	Numbering (old Indian/Defence series)	Usual contour interval
1:1,000,000 (Million sheet)	4° × 4°	Numbered e.g. **55**	—
1:250,000 (degree sheet)	1° × 1°	16 per million sheet, lettered **A–P**, e.g. **55K**	100 m
1:50,000	15′ × 15′	16 per degree sheet, numbered **1–16**, e.g. **55K/7**	**20 m**
1:25,000	7′30″ × 7′30″	4 per 1:50,000 sheet: NE, NW, SE, SW, e.g. **55K/7/NE**	**10 m**

- **National Map Policy 2005**: **Defence Series Maps** (Everest spheroid, polyconic) and **Open Series Maps** for civil use (**WGS-84, UTM**).
- Toposheet colours: water **blue**; forest **green**; contours **brown**; cultivation **yellow**; roads/settlements **red**; railways, grid, lettering **black**.
- **Bench mark** symbol: **broad arrow (crow's foot)** with a bar.

Contours

- **Contour**: line of **equal elevation**. **Contour interval (CI)**: vertical distance between successive contours, kept **constant** on a map. **Horizontal equivalent**: horizontal distance between them (varies with slope).
- CI depends on **ground, scale, purpose, time and cost**; CI is **inversely proportional to scale**.
- Thumb rule: **CI (m) = 25 ÷ (cm per km of map scale)**; old rule 50/(inches per mile) ft. Typical CI: flat building site **0.2–0.5 m**; town planning/reservoir 0.5–2 m.

Contour characteristic	Interpretation
Contours **close together**	**Steep** slope
Widely spaced	Gentle slope or flat ground
Equally spaced, straight and parallel	Uniform slope or plane surface
Closed contours, **higher values inside**	**Hill**
Closed contours, **lower values inside**	**Depression** (pond, lake)
V-shape with the **apex pointing uphill** (towards higher contours)	**Valley**. The stream follows the valley line.

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V/U-shape with the **apex pointing downhill** (towards lower contours)	**Ridge** (watershed)
Contours **crossing** each other	Only at an **overhanging cliff** or cave
Contours **meeting/merging** into one line	**Vertical cliff**
Contour crossing a ridge or valley line	Always at **right angles**

- A contour never ends abruptly (closes in or outside the map). Steepest slope is **normal to the contour**.
- **Direct contouring**: contour points traced in the field with level and staff; **most accurate**, slow; small areas. **Indirect**: spot levels + interpolation by **squares (grid)**, **cross-sections** (roads, canals) or **tacheometry** (hilly areas).
- Uses: route location at a given grade, **intervisibility**, sections, catchment area, **reservoir capacity**, earthwork.
- **UTM**: **60 zones of 6° longitude**, 80° S–84° N, **scale factor 0.9996** on the central meridian, **conformal**; India in zones **42–47**. Old SoI toposheets used **polyconic** projection.

MEMORY TRICK

"**V points to Valley's source**": the V of a valley points uphill towards the source of the stream, and the V of a ridge points downhill. "Close lines = Climb" (steep).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- A diagonal scale can read up to how many dimensions? → **Three**.
- RF of 1 cm = 50 m? → **1/5000**.
- Contours can cross each other only in the case of? → **Overhanging cliff**.
- Contour interval on a 1:50,000 SoI toposheet? → **20 m**.
- In a retrograde vernier, n vernier divisions equal? → **(n + 1) main-scale divisions**.
- The most accurate method of contouring is? → **Direct method**.

11.3 Linear Measurement – Chain & Tape Surveying ★★★

- **Chain surveying**: linear measurements only; principle of **triangulation** (network of well-conditioned triangles). Suited to **small, level, open areas with simple details**.
- Lines: **base line** (longest), main lines, **check (proof) lines** (check framework), **tie lines** (locate interior details).
- **Well-conditioned triangle**: no angle < **30°** or > **120°**; ideal **equilateral (60°)**.

Chain	Length	No. of links	Length of one link
Metric chain (IS 1492)	**20 m** / **30 m** (also 5 m and 10 m)	100 / 150	**0.2 m (20 cm)**
Gunter's (surveyor's) chain	**66 ft**	100	0.66 ft (7.92″)
Engineer's chain	**100 ft**	100	1 ft
Revenue chain	33 ft	16	2 1/16 ft

- Gunter's chain: **10 sq chains = 1 acre**; **80 chains = 1 mile**.
- Metric chain: **brass tallies every 5 m**, small rings every metre; length includes handles. Tolerance: 20 m **±5 mm**, 30 m **±8 mm**.
- Accessories: **arrows** (10 per set, ≈ 400 mm), **ranging rods** (2 or 3 m, 20 cm bands), offset rod (3 m), pegs, plumb bob.

Tape	Remarks
Cloth / linen	Stretches and shrinks; for offsets only
Metallic	Linen with brass/copper wires woven in; for offsets and ordinary work
Steel	Accurate; for precise work. $\alpha \approx 11.5 \times 10^{-6}$ /°C
Invar	**Ni 36% + steel**. Very **low coefficient of expansion** (≈ 1/10th or less of steel, ≈ $0.1–1 \times 10^{-6}$ /°C). Used for **base line measurement** in triangulation. Soft and costly.
Synthetic / fibreglass	Non-conducting; for general work

- **Ranging**: **direct** (ends intervisible) or **indirect = reciprocal** (ends **not intervisible**, e.g. across a hill).
- **Chaining on slope**: direct (**stepping**, downhill, with plumb bob) or indirect (measure θ or h). **Hypotenusal allowance** = 100(sec θ − 1) links per chain.
- **Offsets**: **perpendicular** (cross staff, optical/prism square) or **oblique**. **Limiting length of offset**: beyond it the plotting error exceeds **≈ 0.25 mm** on paper.
- **Cross staff**: open (90°), **French** (octagonal, **45° and 90°**), adjustable (any angle).
- **Optical square**: two mirrors at **45°**; double reflection deviates the ray by **twice the mirror angle = 90°**. Prism square: same principle, needs no adjustment.
- **Obstacles**: (a) chaining obstructed, vision free (pond, river); (b) vision obstructed, chaining free (rising ground → reciprocal ranging); (c) both obstructed (building).
- Field book is written from **bottom to top**.

Tape corrections

Correction	Formula	Sign
Standardisation (absolute)	$C_a = L \cdot c/l$ (c = error per tape length l)	+ if the tape is too long; − if too short
Temperature	$C_t = \alpha L (T_m - T_0)$	+ if $T_m > T_0$
Pull (tension)	$C_p = (P - P_0) L/(A E)$	+ if $P > P_0$
Sag	$C_s = \mathbf{W^2 L/(24 P^2)} = \mathbf{w^2 L^3/(24 P^2)}$ (W = wL = total weight of span)	**Always −**
Slope	$C = \mathbf{L(1 - \cos\theta) \approx h^2/(2L)}$	**Always −**
Reduction to MSL	$C_{msl} = L\ h/R$	− when the line is above MSL

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Alignment	$d^2/(2L)$	Always −

- **Normal tension**: pull at which **pull and sag corrections cancel**: $P_n = 0.204\ W\ \sqrt{(AE)}/\sqrt{(P_n - P_0)}$ (by trial).

KEY FORMULAE

- True length = (l′/l) × measured length (l′ = actual length of the chain, l = nominal length)
- True area = $(l'/l)^2$ × measured area. True volume = $(l'/l)^3$ × measured volume
- If the chain is **too long**, measured lengths are **too short** (the error is negative), so the true length is greater.
- Slope correction = $h^2/2L + h^4/8L^3 + \ldots \approx h^2/2L$

MEMORY TRICK

"**Sag, Slope, Sea – always Subtract**": the sag, slope and MSL corrections (for lines above MSL) are negative. Temperature, pull and standardisation can be + or −.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Length of one link of a 20 m metric chain? → **0.2 m**.
- A 20 m chain was found 10 cm too long; measured length 400 m. True length? → 400 × 20.1/20 = **402 m**.
- Slope correction for 30 m length with 1.5 m height difference? → $1.5^2/(2 \times 30)$ = **0.0375 m (subtractive)**.
- Indirect ranging is also called? → **Reciprocal ranging**.
- Angle between the mirrors of an optical square? → **45°**.
- Normal tension is the pull at which? → **Pull correction = sag correction**.

11.4 Compass Surveying ★★★

- Meridians: **true** (geographic poles, fixed), **magnetic** (free needle, varies), arbitrary, grid.
- **WCB**: **clockwise from north**, 0°–360° (**prismatic compass**). **QB/RB**: from **N or S** towards E or W, 0°–90°, e.g. N 30° E (**surveyor's compass**).
- **FB and BB differ by exactly 180°** (WCB). In RB the value is the same, letters swap: BB of N 30° E = **S 30° W**.

WCB range	Quadrant	RB	Example
0°–90°	NE	N θ E (RB = WCB)	40° → N 40° E
90°–180°	SE	S (180° − θ) E	130° → S 50° E
180°–270°	SW	S (θ − 180°) W	210° → S 30° W
270°–360°	NW	N (360° − θ) W	300° → N 60° W

Feature	Prismatic compass	Surveyor's compass
Needle	**Broad needle**. It does not act as the index.	**Edge-bar needle**. It acts as the index.
Graduated ring	Attached to the needle. It **does not rotate** with the line of sight.	Attached to the box. It **rotates with the line of sight**.
Graduations	**WCB**, 0° at the **South end**, clockwise, figures written **inverted**	**QB**, 0° at N and S, 90° at E and W, with **E and W interchanged**, figures erect
Reading	Through a **prism**. Sighting and reading are done **simultaneously**.	Read directly from the top of the glass, **after** sighting
Support	Hand-held or on a tripod	**Tripod essential**
Least count (usual)	**30′** (readings estimated to 15′)	**15′**

- **Magnetic declination**: angle between true and magnetic meridians. **East**: True bearing = **MB + declination**; **West**: TB = MB − declination.
- Variations: **secular** (long period, **largest**), annual, **diurnal** (more in summer, by day, near poles), irregular (magnetic storms).
- **Dip**: needle's angle with horizontal; **0° at magnetic equator, 90° at magnetic poles**; balanced by a sliding **rider**.
- **Isogonic**: equal declination; **agonic**: **zero declination**; **isoclinic**: equal dip; **aclinic**: zero dip.
- **Local attraction** (iron, cables, ore): **detected** when FB and BB do not differ by 180°. It shifts **all bearings at that station by the same amount**. Correct by starting from a line whose FB − BB = 180°, or via included angles (unaffected).

KEY FORMULAE

- BB = FB ± 180° (add 180° if FB < 180°; subtract if FB > 180°)
- Included angle at B (clockwise from BC to BA) = BB of AB − FB of BC (add 360° if the result is negative)
- Closed traverse of n sides: Σ interior angles = (2n − 4) × 90°. Σ exterior angles = (2n + 4) × 90°
- Example: FB of AB = 30°, FB of BC = 110°, so ∠ABC = 210° − 110° = **100°**

PREVIOUSLY ASKED / LIKELY QUESTIONS

- WCB of 225° expressed as RB? → **S 45° W**.
- BB of a line with FB N 60° W? → **S 60° E**.
- Line joining points of zero declination? → **Agonic line**.
- Magnetic bearing 140°, declination 5° W; true bearing? → **135°**.
- In a prismatic compass, the zero of the graduated ring is at? → **South end**.
- Local attraction is detected by? → **FB and BB not differing by 180°**.

11.5 Levelling ★★★

- **Datum**: reference surface, in India **MSL**. **RL**: elevation above datum. **Level surface**: normal to the plumb line everywhere.

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- **Line of collimation**: through the cross-hair intersection and optical centre of objective. **HI**: RL of the line of collimation.
- **BS**: **first reading** after setting up, on a point of **known RL** (plus sight). **FS**: **last reading** before shifting (minus sight). **IS**: any reading in between. **Change point**: **both FS and BS** taken.

Bench mark (BM)	Established by / features
GTS BM	**Survey of India**, all over the country, highest precision; published in catalogues
Permanent BM	State agencies (PWD, Irrigation, Railways), between GTS BMs
Arbitrary BM	RL assumed (e.g. 100.000 m) for small works
Temporary BM	At the end of a day's work, to resume next day

Level	Key features
Dumpy level	Telescope **rigidly fixed** to the vertical spindle. Simple, stable, keeps its adjustments longer.
Wye (Y) level	Telescope removable from Y supports; quick to adjust, goes out of adjustment quickly
Tilting level	Telescope tilts by a **tilting screw**; vertical axis need not be exactly vertical; precise work
Automatic level	Optical **compensator** makes sight horizontal after rough levelling
Digital level	Reads a **bar-coded staff** electronically

- **Temporary adjustments**: (1) setting up; (2) **levelling up** with foot screws; (3) **elimination of parallax**: focus the **eyepiece** first (cross-hairs), then the **objective** (staff).
- **Permanent adjustments (dumpy)**: (1) bubble tube axis ⊥ vertical axis; (2) **line of collimation ∥ bubble tube axis**: the **fundamental relation**, checked by the **two-peg test**; (3) horizontal hair ⊥ vertical axis.
- **Staff**: self-reading (solid, folding, telescopic **Sopwith**) or target staff. Graduations **5 mm** (LC 0.005 m). An inclined staff always reads **too large**; rock it and note the **minimum**.

Point	HI (Height of Instrument / collimation) method	Rise & Fall method
Principle	HI = RL of BM + BS. RL = HI − (IS or FS)	Difference of consecutive readings: rise if the earlier reading is larger, fall if smaller
Arithmetic check	ΣBS − ΣFS = last RL − first RL	**ΣBS − ΣFS = ΣRise − ΣFall = last RL − first RL**
Check on intermediate RLs	**No**	**Yes**. A complete check.
Speed	Faster, less tedious	Slower, more calculation
Best for	Profile levelling, contouring, construction (many IS)	Fly/check levelling, precise work (few IS)

- **Larger staff reading = lower point. Equal BS and FS distances** eliminate **collimation, curvature and refraction** errors.
- **Reciprocal levelling**: when the level cannot be set midway (**across a river/valley**). Eliminates **collimation, curvature and refraction** errors (not a change in refraction between readings).
- **Types**: differential; **fly** (quick, approximate, e.g. bringing a BM to site); **check** (closing back on the starting BM); **profile/L-section** (along centre line); **cross-sectioning**; precise; **trigonometric** (vertical angles); **barometric**; **hypsometry** (**boiling point of water**).
- **Bubble sensitivity**: angle tilted per one division (≈ 2 mm) of bubble movement. Increases with **larger radius**, larger diameter and length, lower viscosity. Liquid: **spirit or ether**.
- **Errors**: instrumental (collimation, sluggish bubble, staff), natural (curvature, refraction, wind, settlement), personal (parallax, staff not vertical, booking).

KEY FORMULAE (D IN KM, CORRECTION IN M)

- Curvature correction $C_c = d^2/2R$ = **0.0785 d²** (subtractive; it makes objects appear lower)
- Refraction correction $C_r = (1/7)\ C_c$ = **0.0112 d²** (additive)
- Combined correction $C = (6/7)\ C_c$ = **0.0673 d²** (subtractive)
- Distance to visible horizon $d = \sqrt{(h/0.0673)}$ = **3.855 √h** km (h in m). Example: h = 36 m gives d ≈ 23.1 km
- Reciprocal levelling: true difference $H = [(a_1 - b_1) + (a_2 - b_2)]/2$. Combined error $e = [(a_1 - b_1) - (a_2 - b_2)]/2$
- Bubble sensitivity $\alpha'' = s/(n\ D) \times 206265$. Radius of tube $R = n\ l\ D/s$ (s = difference in staff readings, n = divisions moved, l = length of one division, D = distance to staff)
- Permissible closing error (Punmia): rough $\pm 100\sqrt{K}$ mm. Ordinary $\pm 24\sqrt{K}$ mm. Accurate $\pm 12\sqrt{K}$ mm. Precise $\pm 6\sqrt{K}$ mm (K = distance in km)

MEMORY TRICK

"**785 – 112 – 673**": Curvature 0.0785, Refraction 0.0112, Combined 0.0673 (each × d²). Refraction is **1/7** of curvature, so combined = 6/7 × curvature. **C**urvature **C**uts (−), **R**efraction **R**aises (+).

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- Combined correction for curvature and refraction at 2 km? → 0.0673 × 4 = **0.269 m**.
- Arithmetic check in rise & fall method? → **ΣBS − ΣFS = ΣRise − ΣFall = Last RL − First RL**.
- Reciprocal levelling eliminates? → **Collimation, curvature and refraction errors**.
- Fundamental relation of a dumpy level? → **Line of collimation ∥ axis of bubble tube**.
- Two-peg test is used for? → **Collimation adjustment of a level**.
- BM established by Survey of India throughout the country? → **GTS bench mark**.

11.6 Theodolite, Traversing & Tacheometry ★★★

- **Theodolite**: measures **horizontal and vertical angles**; also prolonging lines, tacheometry, setting out curves.
- **Vernier transit theodolite**: MSD **20′**, 60 vernier divisions → **LC = 20″**. Size = **diameter of the lower graduated plate**. Micrometer/optical types (e.g. Wild T2) read to **1″**.
- **Transit**: telescope can revolve 180° in the vertical plane; non-transit cannot.
- Parts: trivet, tribrach and levelling head (3 foot screws), lower (scale) plate, upper (vernier) plate with verniers **A and B at 180°**, plate levels, standards (A-frame), telescope, vertical circle with altitude bubble, upper and lower clamps + tangent screws, plumb bob/optical plummet.

Term	Meaning
Face left (normal)	The vertical circle is on the **left** of the observer when sighting
Face right	The vertical circle is on the right
Transiting (plunging / reversing)	Turning the telescope through **180° about the horizontal (trunnion) axis**
Swinging	Turning the telescope about the **vertical axis**. Right swing = clockwise, left swing = anticlockwise.
Changing face	Transit, then swing through 180°

- **Temporary adjustments**: setting up, **centring**, **levelling**, **focusing** (parallax).
- **Fundamental lines**: vertical axis, horizontal (trunnion) axis, line of collimation, plate level axis, altitude level axis.

Required relation	Permanent adjustment
Plate level axis ⊥ vertical axis	**Plate level test**
Line of collimation ⊥ horizontal axis	**Cross-hair (collimation) test**
Horizontal axis ⊥ vertical axis	**Spire test**
Altitude level axis ∥ line of collimation; vertical circle reads 0° when sight is horizontal	**Vertical index test**

- **Face left + face right** removes: collimation ⊥ horizontal axis error, horizontal axis ⊥ vertical axis error, vertical circle **index error**. Reading **both verniers** removes **eccentricity**.
- **Vertical axis not truly vertical** is **NOT eliminated** by changing face.

Repetition method	Reiteration (direction) method
A single angle is measured several times by adding it up on the circle, then mean = total ÷ n	Several angles at one station are measured successively from a reference station, ending back at it (**closing the horizon**)
Gives accuracy **finer than the LC**. Reduces graduation, eccentricity and reading errors.	Σ angles round a station = 360°
Usual: 3 repetitions face left + 3 face right	Used in **triangulation** where many angles meet at a station

Traversing

- **Closed traverse** (loop, or between known points) can be checked. **Open traverse** (roads, canals, coasts) has **no direct check**.
- Methods: chain; chain and compass (**free/loose needle**, errors do not accumulate); theodolite **fast needle**; included or **deflection angles** (best for route surveys).
- **Latitude** L = l cos θ (+N, −S); **Departure** D = l sin θ (+E, −W). Closed traverse: **ΣL = 0, ΣD = 0**.
- **Consecutive coordinates**: L and D of each line. **Independent coordinates**: from a common origin. **Gale's traverse table** computes **independent coordinates**.
- **Omitted measurements**: up to **two** unknowns (length/bearing of one or two sides) found from ΣL = ΣD = 0, assuming the rest is **error-free**.

Balancing rule	Correction	When used
Bowditch (compass) rule	Correction to L or D of a line ∝ **length of that line**: $C_L = \Sigma L \times (l/\Sigma l)$	Linear and angular measurements of **equal precision** (compass traverse). The most common rule.
Transit rule	Correction ∝ **latitude (or departure) of that line**: $C_L = \Sigma L \times \lvert L\rvert / \Sigma\lvert L\rvert$	**Angular measurements more precise** than linear (theodolite traverse)
Graphical (Bowditch)	Distributed in proportion to distance from start	Compass traverse plotted directly

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KEY FORMULAE

- Closing error $e = \sqrt{[(\Sigma L)^2 + (\Sigma D)^2]}$; $\tan \delta = \Sigma D / \Sigma L$. Relative precision = e/P = 1 in (P/e)
- Trapezoidal rule $A = d[(O_1 + O_n)/2 + O_2 + \ldots + O_{n-1}]$
- Simpson's rule $A = (d/3)[(O_1 + O_n) + 4(\Sigma \text{ even ordinates}) + 2(\Sigma \text{ remaining odd ordinates})]$. It needs an **odd number of ordinates** (even number of divisions). It assumes a **parabolic boundary** and is more accurate.
- Coordinate method: $2A = |\Sigma(x_i\, y_{i+1} - x_{i+1}\, y_i)|$; also DMD method
- Planimeter (Amsler polar): A = M(F − I ± 10N + C). M = multiplying constant (area per revolution of the wheel); C is added only when the anchor is **inside** the figure; M × C = area of the **zero circle**
- Volume, trapezoidal (average end area): $V = d[(A_1 + A_n)/2 + A_2 + \ldots + A_{n-1}]$
- Volume, prismoidal: $V = (d/3)[(A_1 + A_n) + 4\Sigma \text{ even} + 2\Sigma \text{ odd}]$ (odd number of sections). It is more accurate; the trapezoidal method usually **overestimates**
- Prismoidal correction (level sections, side slope s:1) $C_p = (d/6)\, s\, (h_1 - h_2)^2$, subtracted from the trapezoidal volume

Tacheometry, EDM & Total Station

- **Tacheometry**: distances found **optically**, no chaining; for **hilly terrain, contouring**, preliminary surveys (accuracy ≈ 1 in 500–1000).
- Systems: **stadia** – **fixed hair** (most common) or movable hair (subtense); **tangential** (two vertical angles, no stadia hairs); range finding.
- **K = f/i = 100** (multiplying constant). **C = f + d** (additive; ≈ 0.3–0.6 m for external focusing).
- **Anallactic lens**: extra **convex** lens in an **external-focusing** telescope; makes **C = 0**, putting the vertex of the tacheometric angle at the **instrument centre**. Internal-focusing telescopes have C ≈ 0.
- **EDM**: measures **phase difference** of a modulated wave. **Microwave** (**Tellurometer**, long range), **visible light** (**Geodimeter**), **infrared** (**Distomat**, short range, prism reflector).
- **Total station = electronic theodolite + EDM + microprocessor**. Measures angles and slope distance; computes horizontal distance, elevation, **coordinates (N, E, Z)**. Typical ±(2 mm + 2 ppm); reflectorless and robotic types.

KEY FORMULAE – STADIA (FIXED HAIR)

- Line of sight horizontal: **D = K s + C** (s = staff intercept = top − bottom hair)
- Inclined sight, staff **vertical**: $D = K s \cos^2\theta + C \cos\theta$. $V = K s (\sin 2\theta)/2 + C \sin\theta$
- Inclined sight, staff **normal** to the line of sight: $D = (Ks + C)\cos\theta + h \sin\theta$. $V = (Ks + C)\sin\theta$
- RL of staff station = HI ± V − h (h = axial hair reading; + for angle of elevation)
- Tangential (both angles of elevation): $D = s/(\tan\theta_1 - \tan\theta_2)$
- Subtense bar (2 m): $D = (b/2)\cot(\alpha/2) = \cot(\alpha/2)$ for b = 2 m
- EDM: $2D = n\lambda + \Delta\lambda$

MEMORY TRICK

"**Bowditch = Both equal; Transit = Theodolite angles better**". In Bowditch, corrections follow the **length** of the line; in the transit rule they follow the **latitude/departure**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Least count of a vernier theodolite (MSD 20′, 60 vernier divisions)? → **20″**.
- Rotating the telescope 180° about the horizontal axis is called? → **Transiting (plunging)**.
- Bowditch rule assumes? → **Angular and linear errors are equally precise**.
- Simpson's rule needs? → **Odd number of ordinates**.
- Staff intercept 1.5 m, K = 100, C = 0, horizontal sight. Distance? → **150 m**.
- Function of the anallactic lens? → **Makes the additive constant zero**.

11.7 Triangulation & Trilateration ★★☆

- **Triangulation**: measure a **base line** and **all angles**; sides computed by the **sine rule**. Used for large-area control (GTS).
- Figures: **chain of triangles** (narrow strips, least accurate), **braced quadrilaterals** (**strongest**), **centred polygons** (wide areas).
- **Best triangle**: **isosceles with base angles 56°14′**; in practice equilateral, angles 30°–120°.
- **Strength of figure** $R = [(D - C)/D]\, \Sigma(\delta_A^2 + \delta_A\delta_B + \delta_B^2)$ (D = directions observed, C = conditions). **Smaller R = stronger figure**.

Item (Punmia)	Primary (1st order)	Secondary (2nd order)	Tertiary (3rd order)
Length of base line	8–12 km	1.5–5 km	0.5–3 km
Length of sides	16–150 km	8–65 km	1.5–10 km

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Average triangular closure	**< 1″**	**3″**	**6″**
Maximum triangular closure	3″	8″	**12″**
Accuracy of base	1 in 300,000	1 in 150,000	1 in 75,000

- **Base line**: level, unobstructed site; measured with **invar tapes/wires** (Jaderin's method) or EDM; corrected for temperature, pull, sag, slope and **reduction to MSL**; lengthened by **base extension**.
- **Satellite station**: used when the true station (spire, chimney) cannot be occupied; observations corrected by **reduction to centre**.
- **Signals**: **luminous** (sun: **heliotrope**, heliograph; night lamps) or **opaque** (pole, cairn, beacon). **Phase of signal**: error when sunlight lights only part of a cylindrical signal.
- **Bilby tower**: portable steel tower of two independent towers – **inner for instrument, outer for observer**.
- **Intervisibility**: h = 0.0673 d^2. **Trilateration**: **all sides measured** (EDM), angles by cosine rule.

Plane table surveying

- Plotting is done **in the field** (no field book); suited to **small-scale mapping** and magnetic areas; unsuited to wet weather and accurate work.
- Accessories: board, **alidade**, trough compass, spirit level, **plumbing fork (U-frame)**, paper.
- Set-up: **levelling, centring, orientation**. Orientation by trough compass (approximate), **back sighting (most accurate)** or resection.

Method	Use
Radiation	All points visible from one station. Rays are drawn and distances measured. Small areas.
Intersection (graphical triangulation)	Points located by rays from two stations. Used for **inaccessible points**, broken boundaries and hill tops. Only the base is measured.
Traversing	Like a compass traverse. Used for roads and rivers.
Resection	Finding the position of the **table's own station** on paper by sighting known (plotted) points

- **Two-point problem**: needs an auxiliary station; less accurate.
- **Three-point problem**: (1) **tracing paper** (mechanical); (2) **Bessel's** (graphical); (3) **Lehmann's** (trial and error, reducing the **triangle of error**). Indeterminate if the station lies on the **danger circle** through the three points.

Photogrammetry basics

- **Terrestrial** (phototheodolite) or **aerial** (vertical: tilt < 3°; oblique).
- **Forward overlap ≈ 60%** (for stereo); **side lap ≈ 25–30%**. Principal point located by **fiducial marks**. **Crab**: camera not square to flight line; **drift**: aircraft blown off line.
- **Relief displacement**: **radial from the nadir**, **zero at the nadir**. Heights from **parallax bar**.

KEY FORMULAE

- Scale of vertical photo S = f/(H − h) (f = focal length, H = flying height above datum, h = ground elevation)
- Relief displacement d = r h/H (r = radial distance of the image from the principal point; h = object height)
- Example: f = 150 mm, H − h = 3000 m, so S = 0.15/3000 = **1:20,000**

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Strongest triangulation figure? → **Braced quadrilateral**.
- Best shape of triangle in triangulation? → **Isosceles with base angles 56°14′**.
- Bilby tower is used in? → **Triangulation (elevating instrument and signal)**.
- Three-point problem can be solved by? → **Tracing paper, Bessel's, Lehmann's methods**.
- Most accurate orientation of a plane table? → **Back sighting**.
- Usual forward overlap of aerial photographs? → **60%**.

11.8 Curves – Horizontal & Vertical ★★★

- **Horizontal curves**: simple, compound, reverse, transition. **Vertical curves**: summit and valley.
- **T_1 = point of curve (PC)**, **T_2 = point of tangency (PT)**, V = **PI**. **Deflection angle Δ = central angle**; **intersection angle I = 180° − Δ**.
- **Degree of curve D**: angle at the centre subtended by a standard 30 m (or 20 m) arc/chord. **Higher D = sharper curve**.

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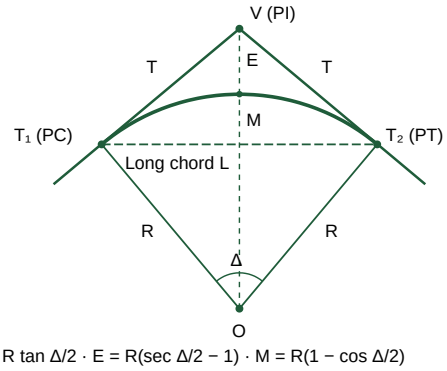

$T = R \tan \Delta/2 \cdot E = R(\sec \Delta/2 - 1) \cdot M = R(1 - \cos \Delta/2)$

Fig. 11.1 Elements of a simple circular curve (central angle at O = deflection angle Δ)

KEY FORMULAE – SIMPLE CIRCULAR CURVE

- Tangent length T = **R tan(Δ/2)**
- Length of curve l = **πRΔ/180** (Δ in degrees)
- Long chord L = **2R sin(Δ/2)**
- Mid-ordinate (versed sine) M = **R(1 − cos Δ/2)**
- External (apex) distance E = **R(sec Δ/2 − 1)**
- Degree of curve, 30 m arc: **R = 1718.9/D ≈ 1719/D**. 20 m arc: **R = 1145.9/D ≈ 1146/D** (R in m, D in degrees). 100 ft arc: R = 5729.6/D ft
- Chainage of T_1 = chainage of PI − T. Chainage of T_2 = chainage of T_1 + l (**not** PI + T)
- Rankine's deflection angle **δ = 1718.9 c/R minutes** (= 28.65 c/R degrees). Total deflection $\Delta_n = \Delta_{n-1} + \delta_n$. Check: the last total deflection = **Δ/2**
- Offsets from the long chord: $O_x = \sqrt{(R^2 - x^2)} - (R - M)$. Mid-ordinate $O_0 = M$
- Offsets from the tangent: radial $O_x = \sqrt{(R^2 + x^2)} - R$. Perpendicular $O_x = R - \sqrt{(R^2 - x^2)} \approx x^2/2R$
- Offsets from chords produced: $O_1 = c_1^2/2R$. $O_n = c_n(c_{n-1} + c_n)/2R$

- **Example**: PI at 1000 m, Δ = 60°, R = 300 m → T = **173.21 m**, l = **314.16 m**, T_1 at **826.79 m**, T_2 at **1140.95 m**.
- Normal chord 20 or 30 m (≤ R/20); first and last are **sub-chords**.

Setting-out method	Instruments	Remarks
Offsets from long chord / tangents, successive bisection of arcs	Chain/tape only (**linear methods**)	Short curves of large radius, low accuracy
Offsets from chords produced	Tape	Errors accumulate
Rankine's method (deflection angles)	**One theodolite + tape**	Most common, accurate
Two-theodolite method	Two theodolites, **no tape**	Rough ground; points by intersection

- **Compound curve**: arcs of **different radii** bending in the **same direction**. **Reverse curve**: arcs bending in **opposite directions**; avoided at high speeds (superelevation must reverse suddenly).
- **Transition curve**: radius changes gradually (∞ → R), introducing centrifugal force and superelevation gradually. **Ideal = clothoid (spiral)**, **l·r = constant** (IRC recommends it). **Cubic parabola** $y = x^3/(6RL)$: **railways**. **Bernoulli's lemniscate**: highways, large deflection angles.

KEY FORMULAE – TRANSITION & VERTICAL CURVES

- Shift of circular curve S = **$L^2/(24R)$** (L = length of transition)
- Spiral angle $\varphi_s = L/(2R)$ radians. Total tangent length = (R + S) tan(Δ/2) + L/2
- Length by rate of change of centrifugal acceleration (IRC): $L_s = v^3/(C\,R)$, with $C = 80/(75 + V)$ m/s³, 0.5 ≤ C ≤ 0.8 (v in m/s, V in km/h)
- Length by rate of introducing superelevation: 1 in 150 (plain/rolling), 1 in 60 (hilly)
- Empirical (IRC): plain/rolling $L_s = 2.7V^2/R$. Hilly $L_s = V^2/R$
- Vertical curve length $L = (g_1 - g_2)/r$ (r = rate of change of grade per station). Deviation angle N = algebraic difference of grades
- Tangent offset of a parabola $y = (g_1 - g_2)\,x^2/(2L)$. Highest/lowest point at $x = g_1L/(g_1 - g_2)$
- Summit curve (IRC, L > SSD): $L = N\,S^2/4.4$ (driver's eye height 1.2 m, object 0.15 m)
- Valley curve (headlight, L > S): $L = N\,S^2/(1.5 + 0.035\,S)$

- Vertical curves are **parabolic**: **constant rate of change of grade**, offsets ∝ x^2. **Summit** curves are designed for **sight distance**; **valley** curves for **comfort and headlight distance** (cubic parabola preferred on highways).
- Railways allow a **smaller rate of change of grade at sags than at summits** (commonly 0.05% vs 0.1% per chain).

MEMORY TRICK

"**1719 for 30, 1146 for 20**": R × D = 1719 (30 m arc) or 1146 (20 m arc). The deflection constant 1718.9 is the same number, but in minutes: δ = 1718.9 c/R. "**Shift = L squared over 24 R**", the same 24 as in the sag formula $w^2L^3/24P^2$.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Radius of a 2° curve (30 m arc)? → 1719/2 ≈ **859.5 m**.
- Tangent length of a curve, R = 200 m, Δ = 90°? → **200 m**.
- Shift of a transition curve of length 60 m on R = 300 m? → 3600/7200 = **0.5 m**.
- Ideal transition curve? → **Clothoid (spiral)**.
- Rankine's method of setting out uses? → **Theodolite and tape (deflection angles)**.
- Shape of vertical curves? → **Parabola** (constant rate of change of grade).

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11.9 Remote Sensing, GIS & GPS ★★★

Remote sensing

- **Remote sensing**: information without contact, by recording **reflected or emitted EMR**.
- **Passive** sensors use natural energy (reflected sunlight, emitted heat): LISS, cameras. **Active** sensors send their own energy: **RADAR/SAR**, **LiDAR**; work **day and night**, microwave penetrates **clouds**.
- Healthy vegetation: **high NIR reflectance**, absorbs blue and red (chlorophyll). Water is **dark in NIR**. In a **standard FCC**, vegetation appears **red**.
- **NDVI = (NIR − Red)/(NIR + Red)**, range **−1 to +1** (water negative).
- **Geostationary**: ≈ **35,786 km**, 24 h period (INSAT/GSAT, weather). **Sun-synchronous polar**: ≈ 600–900 km, crosses the equator at the **same local time** (IRS).
- Interpretation elements: tone, texture, shape, size, pattern, shadow, site, association.

EM band	Wavelength	Use
Visible	**0.4–0.7 µm** (blue 0.4–0.5, green 0.5–0.6, red 0.6–0.7)	Panchromatic and true-colour images
Near IR (NIR)	0.7–1.3 µm	**Vegetation** health, water–land boundary
Short-wave IR (SWIR)	1.3–3 µm	Soil and leaf moisture, minerals
Thermal IR	**8–14 µm**	Surface temperature, emitted energy
Microwave	1 mm – 1 m	**RADAR/SAR**, all-weather, soil moisture

Resolution	Meaning	Example
Spatial	Size of the smallest object resolved (pixel size / IFOV)	Cartosat-3 PAN ≈ 0.25 m
Spectral	Number and width of wavelength bands	Panchromatic (1 band) < multispectral (3–10) < **hyperspectral** (100s of narrow bands)
Radiometric	Sensitivity to differences in energy, i.e. the number of grey levels (bits)	**8-bit = 256 levels**; 10-bit = 1024; 11-bit = 2048
Temporal	Revisit time over the same area	Resourcesat LISS-III: 24 days; AWiFS: 5 days

Indian satellite	Key facts
IRS-1A (17 Mar 1988)	**First operational Indian Remote Sensing satellite** (Soviet Vostok launcher)
Resourcesat-1/2/2A (2003/2011/2016)	Resource mapping. **LISS-IV 5.8 m**, **LISS-III 23.5 m**, **AWiFS 56 m**
Cartosat-1 (2005)	**Two PAN cameras, along-track stereo**, 2.5 m; CartoDEM
Cartosat-3 (2019)	PAN ≈ **0.25 m**, highest-resolution Indian civil imager (Cartosat-2 series: sub-metre)
RISAT-2 (2009) / RISAT-2B (2019)	**X-band SAR** (RISAT-2 built with Israel)
RISAT-1 (2012)	First indigenous **C-band SAR**; successor **EOS-04 (RISAT-1A)**, 2022
NISAR (30 Jul 2025, GSLV-F16)	NASA–ISRO SAR, **L-band (NASA) + S-band (ISRO)**

- **Bhuvan** (2009): ISRO's **geoportal** by **NRSC, Hyderabad**; imagery, thematic maps, geotagging (MGNREGA, PMAY). **IIRS** is at Dehradun.

GIS

- **GIS**: system to **capture, store, query, analyse and display spatial data**. **Five components**: **hardware, software, data, people, methods**.
- **Spatial data** (geometry) + **attribute data** (tables) linked by a common ID.
- **Topology**: **connectivity** (arc–node), **adjacency** (left/right polygon), **containment**.
- Analysis: **overlay** (union, intersect, clip; site suitability), **buffer** (zone at a set distance around a feature), network (shortest route), interpolation (IDW, kriging).
- **DEM**: bare-earth elevation raster. **DSM**: includes buildings/trees. **TIN**: **vector** model of Delaunay triangles on irregular points (denser in rough terrain).
- **Georeferencing**: giving real-world coordinates to an image/map using **GCPs**, then **resampling** (nearest neighbour, bilinear, cubic). GPS datum: **WGS-84**.
- Software: **ArcGIS** (ESRI), **QGIS** (open source), GRASS, **ERDAS Imagine**, ENVI. Formats: **shapefile** (.shp/.shx/.dbf, vector), **GeoTIFF** (raster), KML.

Raster model	Vector model
Space is a grid of **cells (pixels)**. Each cell holds a value.	Features are **points, lines (arcs) and polygons** stored as x, y coordinates
Simple data structure. **Overlay and analysis are easy and fast.**	**Compact** storage, **accurate geometry**, explicit **topology**
Large file size. Accuracy depends on cell size ("blocky" look).	Complex structure. Overlay is computationally heavy.
Best for **continuous data**: satellite images, DEM, temperature, land use	Best for **discrete features**: boundaries, roads, pipelines, cadastral parcels, networks
Compression: run-length encoding, quadtree	Structures: spaghetti, arc–node (topological)

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GNSS / GPS

- **GPS (NAVSTAR)**: US **Department of Defense**. Segments: **space** (satellites), **control** (Master Control Station, Schriever SFB, Colorado), **user** (receivers).
- Position by **trilateration of pseudoranges**. **Minimum 4 satellites** for a 3-D fix: unknowns **x, y, z and receiver clock bias**.
- Errors: satellite clock and orbit, **ionospheric delay** (usually largest; removed by dual frequency), tropospheric, **multipath** (reflections from buildings/water), receiver noise. **Selective Availability** switched off on **1 May 2000**.
- **DOP**: effect of satellite geometry (GDOP, **PDOP**, HDOP, VDOP). **Lower is better**; widely spread satellites give low DOP.
- **DGPS**: base at a **known point** sends corrections → ~sub-metre to 1–3 m. **RTK**: **carrier-phase**, base + rover via radio/NTRIP → **1–2 cm in real time**. **CORS**: permanent bases (SoI national network). Static relative surveys give **mm-level** accuracy.

GPS parameter	Value
Satellites	**24 nominal** (about 31 operational)
Orbital planes / inclination	**6 planes**, **55°**
Altitude	≈ **20,200 km** (MEO)
Orbital period	≈ **12 h** (11 h 58 min, half a sidereal day)
Frequencies	**L1 = 1575.42 MHz** (C/A and P(Y) codes), **L2 = 1227.60 MHz**, L5 = 1176.45 MHz
Datum	**WGS-84**
Minimum satellites for 3-D fix	**4**

System	Country	Key facts
GPS	USA	Global, 6 planes, ~20,200 km
GLONASS	Russia	Global, 24 satellites, **3 planes**, ~19,100 km
Galileo	European Union	Global, **civilian-controlled**, 3 planes, ~23,222 km
BeiDou (BDS)	China	Global, mix of GEO, IGSO and MEO satellites
QZSS	Japan	Regional
NavIC (IRNSS)	India (ISRO)	**Regional. 7 satellites: 3 GEO + 4 GSO** (inclined geosynchronous). Covers India and **~1500 km** beyond its boundary. Signals in **L5 and S-band**. Position accuracy better than about 20 m. Second-generation **NVS-01** (May 2023) added the L1 band and carries an indigenous rubidium atomic clock.

- **GAGAN** (GPS Aided GEO Augmented Navigation): India's **SBAS** by **ISRO + AAI** for **civil aviation**; DGCA-certified **2015**; first SBAS for the equatorial region. Others: **WAAS** (USA), **EGNOS** (Europe), **MSAS** (Japan).

Drones, LiDAR, SVAMITVA

- **LiDAR**: **active** laser ranging (NIR ≈ 1064 nm on land; **green 532 nm** for bathymetry); gives a 3-D **point cloud**; **multiple returns** map **bare earth under vegetation**.
- **Drone photogrammetry**: orthomosaics, DSMs, contours; accuracy depends on **GSD** and **GCPs** (RTK/PPK drones need fewer GCPs).
- **Drone Rules 2021**: **Digital Sky** platform; green/yellow/red zones (green: up to **400 ft** without permission). Classes: **nano ≤ 250 g**, micro 250 g–2 kg, small 2–25 kg, medium 25–150 kg, large > 150 kg.
- **SVAMITVA** (Survey of Villages Abadi and Mapping with Improvised Technology in Village Areas): launched **24 April 2020** by the **Ministry of Panchayati Raj**; **Survey of India** maps rural abadi land by **drones**; owners get **property cards**.

MEMORY TRICK

GPS "**24-6-20-12-4**": 24 satellites, 6 planes, 20,200 km, 12-hour orbit, 4 satellites for a fix. NavIC "**3 + 4 = 7, reach 1500**": 3 GEO + 4 GSO = 7 satellites, coverage 1500 km beyond India.

CODE UPDATE

National Geospatial Policy 2022 replaced the restrictive regime of the National Map Policy 2005. SoI **Open Series Maps** (WGS-84/UTM) are the civil standard. **NISAR** (NASA–ISRO, L + S band SAR) was launched on 30 July 2025. NavIC second-generation NVS satellites add the **L1** civil signal.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Minimum number of satellites for 3-D GPS position? → **4**.
- Number of satellites in NavIC? → **7 (3 GEO + 4 GSO)**.
- Number of grey levels in 8-bit radiometric resolution? → **256**.
- Which data model is best for continuous surfaces like elevation? → **Raster** (TIN is the vector alternative).
- Zone created at a fixed distance around a feature in GIS? → **Buffer**.
- Sensor type that works through clouds, day and night? → **Active microwave (SAR)**.

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12. Project Management, Planning, Estimating & Contracts

NOTE

This chapter usually gives **6–8 MCQs**. Most of them come from CPM/PERT (floats, t_e, σ, probability, cost slope), estimating (IS 1200 units, deduction rules, bags of cement, $D^2/162$), contract types and earthmoving equipment. As an Assistant Manager in CWC you will also handle tenders, measurement books and warehouse works, so learn GFR, EMD and contract clauses well.

12.1 Project Management Basics ★★☆

- **Project** = a **temporary** effort with a definite start and finish that produces a **unique** result. Its three constraints (the **triple constraint**) are **time, cost and quality/scope**.
- **Project life cycle** = **Concept/Initiation → Feasibility & planning (DPR) → Design → Execution/Construction → Commissioning/Handover → Closure**. Effort and cost are highest in execution. The **ability to influence cost is highest at the start** (concept stage).
- **Phases of project management** = **Planning** (**what**, how, in what order) → **Scheduling** (**when**) → **Controlling** (compare actual with plan, correct).
- **Henri Fayol** is the father of **modern (administrative) management**. He gave **14 principles** (unity of command, scalar chain, division of work …) and five functions: **Planning, Organising, Commanding, Co-ordinating, Controlling**.
- **POSDCORB** (**Luther Gulick**, 1937) = **P**lanning, **O**rganising, **S**taffing, **D**irecting, **Co**-ordinating, **R**eporting, **B**udgeting.
- **F.W. Taylor** is the father of **scientific management**. He gave **functional foremanship** (8 foremen) and time-and-motion study.
- **Work Breakdown Structure (WBS)** = a **hierarchical, deliverable-oriented breakdown** of the whole project into smaller parts. The lowest level is the **work package**. Guide: **8/80 rule** (8–80 hours per package).

Organisation type	Key feature	Merit / Demerit
Line (military/scalar)	Authority flows **vertically** from top to bottom	Simplest, quick decisions, clear discipline / top officers overloaded, no specialists
Line & staff	Line officers have authority. **Staff only advise** (they have no command authority).	Expert advice available / conflict between line and staff
Functional (Taylor)	Each specialist controls one function. A worker gets orders from **several bosses**.	Specialisation / **violates unity of command**
Matrix	Project manager + functional manager, so there is **dual reporting**	Best use of resources across many projects / two bosses cause conflict

- **Feasibility study** checks whether a project is technically, economically/financially, environmentally, socially and legally viable. A **pre-feasibility study** comes first. The **DPR (Detailed Project Report)** follows, with design, drawings, estimate, schedule, financial analysis and EIA, and it is the basis for **investment approval/sanction**.
- **Project appraisal** = a critical, independent review of the DPR before funds are committed.

Appraisal criterion	Definition	Accept if
NPV (Net Present Value)	PV of benefits − PV of costs at the discount rate	**NPV > 0**
IRR (Internal Rate of Return)	The discount rate at which **NPV = 0**	IRR > cost of capital (hurdle rate)
BCR (Benefit-Cost Ratio)	PV of benefits ÷ PV of costs	**BCR > 1**
Payback period	Time taken to recover the initial investment	Shorter is better. It **ignores the time value of money** and cash flows after payback.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- POSDCORB was given by? → **Luther Gulick**.
- Organisation in which a worker has more than one boss? → **Functional (Taylor)**, and also matrix.
- Lowest level of the WBS? → **Work package**.
- Discount rate at which NPV = 0? → **IRR**.
- Appraisal method that ignores the time value of money? → **Payback period**.

12.2 Bar Charts & Milestones ★★☆

- **Bar chart / Gantt chart** was developed by **Henry L. Gantt** (c. 1917, during World War I). It has **time on the X-axis** and **activities on the Y-axis**, and the length of each bar = duration of the activity. Progress can be shown by shading the bar.
- **Limitations of the bar chart**: **no interdependencies** shown; cannot identify **critical activities** or floats; unsuitable for large projects; no time uncertainty; hard to update.
- **Milestone chart** = an improved bar chart. Each bar is split by **milestones** (key events, shown as ◇/○ marks) that have zero duration. It is still weak at showing **interrelationships**

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between milestones of different activities. Joining the milestones logically led to **network analysis**.

- **Line of Balance (LOB)** is used for **repetitive works** such as housing units, road km, pipelines and multi-storey floors. It was developed by **Goodyear (1941)** and later used by the US Navy. Each line is plotted as units completed against time, and its **slope = production (delivery) rate**. It helps balance crews so that trades do not clash.
- **Linear scheduling (time–location / time–distance chart)** is used for **linear projects** such as roads, railways, tunnels, canals and pipelines.
- **S-curve** = a plot of **cumulative cost or cumulative % progress against time**. It is S-shaped because work is slow at the start, fast in the middle and slow at the end. It is used for cash-flow forecasting and for comparing planned with actual progress (the basis of EVM).

Technique	Best for	Shows logic?
Gantt / bar chart	Small projects, communication with site staff	**No**
Milestone chart	Key events within activities	Partly
CPM / PERT network	Large, complex projects	**Yes**
LOB	**Repetitive units**	Rate based
S-curve	Cash flow, overall progress	No

MEMORY TRICK

Gantt = Graph without Guts. It shows time but not logic. **LOB = Lots Of Blocks** (repetitive units).

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Main drawback of the bar chart? → **interdependency of activities is not shown**.
- Bar chart was developed by? → **Henry Gantt**.
- Technique suited to a housing colony with 200 identical units? → **Line of Balance**.
- Cumulative cost vs time plot? → **S-curve**.

12.3 Network Analysis – CPM ★★★

- **CPM (Critical Path Method)** was developed in **1957** by **Du Pont & Remington Rand** (Kelley and Walker). It is **deterministic** (one time estimate per activity), **activity-oriented**, and allows time–cost trade-off.
- **Activity** = a task that **consumes time and resources**. It is shown by an arrow (in AOA). Arrow length has **no relation to duration**.
- **Event (node)** = the start or completion of activities. It is an **instant of time** and consumes no time or resources. Events are classed as **merge** (several activities enter), **burst** (several leave), and **initial/terminal**. A network has **one initial and one end event**.
- **Predecessor** = an activity that must finish before the one in question starts. **Successor** = an activity that can start only after it. **Concurrent** = activities that run at the same time.
- **Dummy activity** = a **dashed arrow** with **zero time and zero resources**, needed only in AOA. Types: **logical (dependency) dummy** shows a dependency that cannot otherwise be drawn; **uniqueness (identity/grammatical) dummy** ensures no two activities share the same i–j.
- **Fulkerson's rule** (D.R. Fulkerson) numbers the events so that the **tail number is less than the head number (i < j)**: number the initial event 1, delete its outgoing arrows, number the new initial events 2, 3 ... and repeat. Skip numbering (10, 20 ...) leaves room for later additions.
- **Network errors**: **looping (cycling)** = a closed loop (endless cycle); **dangling** = an activity not connected to the end event; **redundancy** = an unnecessary dummy (dependency already implied).

Feature	AOA (Activity on Arrow)	AON (Activity on Node)
Activity shown by	**Arrow** (i–j)	**Node** (box/circle)
Dummies	**Needed**	**Not needed**
Relationships	Finish-to-start only	**FS, SS, FF, SF** with lags (Precedence Diagramming Method)
Used in	Classical CPM/PERT (PERT is event-based)	Modern software (Primavera, MS Project)

- **Forward pass** (start → end) gives the **earliest times**. At a merge event take the **maximum**: $E_j = \max (E_i + t_{ij})$.
- **Backward pass** (end → start) gives the **latest times**. At a burst event take the **minimum**: $L_i = \min (L_j - t_{ij})$.
- **Event slack** = $T_L - T_E$ (it belongs to events and is the PERT term). **Float** belongs to activities (the CPM term).
- **Critical path** = the **longest path** through the network. Its activities have **zero total float** (when the scheduled finish = earliest finish), and its length = the **minimum project duration**. A network can have **more than one** critical path.
- **Sub-critical path** = the next longest path, with small float. It can become critical if delayed or if the critical path is crashed.
- **Negative float** occurs when the scheduled/contract completion date is earlier than the computed earliest finish, which means the project is behind schedule.

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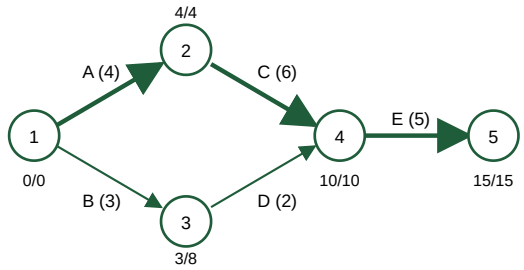
KEY FORMULAE (ACTIVITY I–J, DURATION T)

- EST = E_i ; EFT = EST + t ; LFT = L_j ; LST = LFT − t
- **Total float** TF = LST − EST = LFT − EFT = $L_j - E_i - t$
- **Free float** FF = $E_j - E_i - t$ = $EST_{successor}$ − EFT = TF − (slack of head event)
- **Independent float** IF = $E_j - L_i - t$ (if negative, take it as zero)
- **Interfering float** = TF − FF = head event slack ($L_j - E_j$)
- Order: **TF ≥ FF ≥ IF**

- **TF** = delay possible without delaying the **project**. **FF** = without delaying the **early start of any successor**. **IF** = available even if predecessors **finish latest** and successors **start earliest**. **Interfering float** = part of TF which, if used, **reduces successors' float**.



Worked AOA network. Event labels show T_E/T_L. The thick arrows mark the critical path A–C–E = 15 days.

Activity (i–j)	t	EST	EFT	LST	LFT	TF	FF	IF	Interf.
A (1–2)	4	0	4	0	4	**0**	0	0	0
B (1–3)	3	0	3	5	8	5	**0**	0	5
C (2–4)	6	4	10	4	10	**0**	0	0	0
D (3–4)	2	3	5	8	10	5	**5**	0	0
E (4–5)	5	10	15	10	15	**0**	0	0	0

- **Forward pass**: $E_1 = 0$, $E_2 = 4$, $E_3 = 3$, $E_4 = \max(4 + 6, 3 + 2) =$ **10**, $E_5 =$ **15**.
- **Backward pass**: $L_5 = 15$, $L_4 = 10$, $L_3 = 10 - 2 =$ **8**, $L_2 = 4$, $L_1 = \min(4 - 4, 8 - 3) = 0$.
- **Result**: the critical path is **A–C–E = 15 days**, and event 3 has slack = 8 − 3 = **5**.
- **B** has TF = 5 but FF = 0. All of its float is **interfering**: if B uses it, D loses its float. D, the last activity on that path, has FF = TF = 5.

MEMORY TRICK

Total float: compare with **Late** ($L_j - E_i - t$). **Free** float: **Early–Early** ($E_j - E_i - t$). **Independent** float: "**E**arly head, **L**ate tail" ($E_j - L_i - t$). **Forward = Max, Backward = Min.**

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Duration of a dummy activity? → **Zero** (no time, no resources).
- Rule for numbering events? → **Fulkerson's rule** (tail < head).
- Total float of critical activities? → **Zero**.
- Interfering float = ? → **TF − FF** (= slack of head event).
- A network with a closed path has which error? → **Looping**.
- Network that needs no dummies? → **AON / precedence network**.

12.4 PERT ★★★

- **PERT (Program Evaluation and Review Technique)** was developed in **1958** by the **US Navy Special Projects Office** (with Booz Allen Hamilton and Lockheed) for the **Polaris missile** programme. It is **probabilistic** and **event-oriented**.
- **Three time estimates**: t_o = optimistic (shortest), t_m = most likely (the **mode**), t_p = pessimistic (longest, excluding catastrophes).
- Activity times are assumed to follow the **β (beta) distribution**, which may be unimodal and skewed. The **project duration** (the sum of many activities on the critical path) follows the **normal distribution** by the **Central Limit Theorem**.
- **Project σ** = √(sum of the **variances** of the critical activities). Add the **variances, not the σ's**.
- The probability of completing the project **in exactly the expected time T_E** is **50%**.

KEY FORMULAE

- Expected time $\mathbf{t_e = (t_o + 4t_m + t_p)/6}$
- Standard deviation $\boldsymbol{\sigma = (t_p - t_o)/6}$; variance $\boldsymbol{\sigma^2 = [(t_p - t_o)/6]^2}$
- Project $\sigma_{cp} = \sqrt{(\Sigma\ \sigma^2_{critical})}$
- Probability factor $\mathbf{Z = (T_S - T_E)/\sigma_{cp}}$ (T_S = scheduled/target time)

Z	−3	−2	−1	0	+1	+2	+
Probability of completion	0.13%	2.28%	15.87%	**50%**	**84.13%**	**97.72%**	9

- **Example 1**: $t_o = 2$, $t_m = 5$, $t_p = 14 \rightarrow t_e = 36/6 =$ **6 days**, σ = 12/6 = **2**, variance = **4**.
- **Example 2**: critical path variances are 4, 9 and 3, so σ = √16 = 4. With $T_E = 40$ days and $T_S = 44$ days, Z = (44 − 40)/4 = 1, so P = **84.13%**.

Point	PERT	CPM
Model	**Probabilistic** (3 time estimates)	**Deterministic** (1 time estimate)
Orientation	**Event-oriented**	**Activity-oriented**

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Suited to	**R&D**, new and non-repetitive projects	**Construction**, repetitive projects with known times
Cost	Not considered directly	**Time–cost trade-off (crashing)**
Spare time term	**Slack** (events)	**Float** (activities)
Distribution	β for activities, normal for the project	None
Developed	1958, US Navy (Polaris)	1957, Du Pont

MEMORY TRICK

PERT = Probabilistic, Event, Research. CPM = Cost, Plain (deterministic), Making buildings. Weights in t_e are "**1-4-1 over 6**".

PREVIOUSLY ASKED / LIKELY QUESTIONS

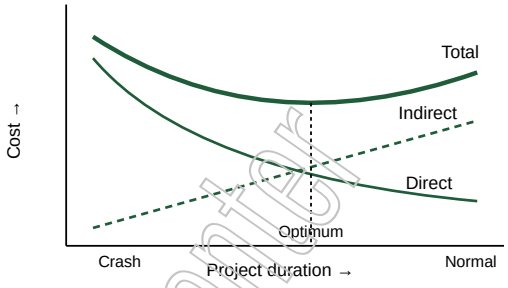
- Distribution assumed for activity times in PERT? → **Beta**.
- If $t_o = 4$, $t_m = 6$, $t_p = 14$, then t_e = ? → **7** ((4 + 24 + 14)/6).
- Probability of finishing the project in its expected time? → **50%**.
- Z = 2 gives what probability? → **≈ 97.7%**.
- PERT is suited to? → **R&D / new projects**.

12.5 Crashing, Resource Levelling & Cost ★★★

- **Direct cost** (labour, materials, equipment of each activity) **increases** when duration is reduced, because overtime, extra crews and costlier methods are needed.
- **Indirect cost** (overheads, supervision, establishment, insurance, interest, penalties) **increases with duration**, roughly in a straight line.
- **Total cost = direct + indirect**. It is a U-shaped curve. Its **minimum point gives the optimum duration** (least-cost duration).
- **Normal time/normal cost** = the duration at the least direct cost.
- **Crash time** = the minimum possible duration of an activity. Spending more cannot reduce it further. **Crash cost** = the direct cost at crash time.
- **Crashing procedure**: crash only **critical activities**, starting with the **least cost slope**; crash by the smaller of the available crash time and the float of parallel paths; when several paths become critical, crash them together; stop when total cost starts rising or all critical paths are fully crashed.
- Crashing a non-critical activity **does not reduce project duration**; it only adds cost.

KEY FORMULAE

- **Cost slope = $(C_c - C_n)/(T_n - T_c)$** (₹ per unit time)
- Example: normal 10 d, ₹5,000 and crash 6 d, ₹7,000 → slope = 2000/4 = **₹500/day**



Time–cost trade-off. Total cost is least at the optimum duration.

Term	Meaning
Resource allocation (resource-constrained scheduling)	Resources are **limited**. Activities are scheduled within the resource limit, so the **project duration may increase**.
Resource levelling	Resources are re-arranged to remove peaks and over-allocation. The duration may change.
Resource smoothing	**Project duration is fixed**. Non-critical activities are shifted **within their floats** to get an even resource histogram.
Updating	The network is revised during execution with the actual progress, and floats and the critical path are recomputed.
Project control	The cycle of plan → monitor → compare → correct. Tools: S-curve, EVM, progress reports.

- Indian textbooks sometimes use "levelling" for what PMBOK calls "smoothing" (fixed duration). In an MCQ, the key distinction is whether the **duration is fixed** (smoothing) or the **resources are fixed** (allocation/levelling).

EVM term	Meaning / formula	Interpretation
PV (BCWS)	Planned value = budgeted cost of work **scheduled**	Baseline
EV (BCWP)	Earned value = budgeted cost of work **performed**	Value of work done
AC (ACWP)	Actual cost of work performed	Money spent
CV	**EV − AC**	−ve = over budget
SV	**EV − PV**	−ve = behind schedule
CPI	**EV/AC**	< 1 = over budget
SPI	**EV/PV**	< 1 = behind schedule
EAC	BAC/CPI (typical case)	Estimate at completion

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VAC	BAC − EAC	Variance at completion

- **Example**: PV = 100, EV = 80, AC = 90 lakh. Then SV = −20, CV = −10, SPI = 0.8, CPI = 0.89, so the project is **behind schedule and over budget**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Which activity is crashed first? → **The critical activity with the least cost slope**.
- Indirect cost as duration increases? → **Increases**.
- Duration at minimum total cost? → **Optimum duration**.
- CPI = ? → **EV/AC**. SPI < 1 means? → **Behind schedule**.
- Shifting activities within float with project duration fixed? → **Resource smoothing**.

12.6 Estimating & Costing ★★★

Type of estimate	Basis / use
Preliminary / approximate / rough	Made at the project stage to get **administrative approval (AA)**. Methods are listed below.
– **Plinth area method**	Plinth area (built-up, covered area at floor level) × plinth area rate. This is the most common method for buildings.
– **Cubic content (cube rate) method**	Volume of the building × cube rate. More accurate for **tall/multi-storey** buildings.
– **Service unit / unit base method**	Cost per unit of service: per **bed** (hospital), per **student** (school), per **km** (road), per tonne of storage capacity (warehouse).
– **Bay method**	Cost per bay. Used for buildings with repeated bays such as **godowns**, factories and bridges.
Detailed estimate	Item-wise quantities × rates (abstract of cost), plus contingencies and work-charged establishment. Needed for **Technical Sanction (TS)**.
Revised estimate	Prepared when the sanctioned estimate is exceeded by more than **5%** (textbook value; the CPWD Works Manual allows a margin of **10%**) or when there is a material deviation.
Supplementary estimate	For **additional work** found necessary during execution, beyond the original scope.
Annual repair (maintenance) estimate	To keep the structure in good condition. Commonly **~1–1.5% of capital cost** for buildings.
Quantity estimate	Only quantities of items, without rates (the basis of a BOQ).
Complete estimate	The total cost of the project, including land, services and other heads.

- **Sanctions**: **Administrative Approval (AA)** on preliminary estimate → **Expenditure Sanction (ES)** → **Technical Sanction (TS)** on detailed estimate → tender.
- **Long wall–short wall method**: long wall (out-to-out) = c/c length **+ one breadth**; short wall (in-to-in) = c/c length **− one breadth**.
- **Centre-line method**: total centre-line length × cross-section. For **each T-junction**, deduct **½ × breadth** of the wall from the total centre-line length. **Corners need no deduction.** It is quick for walls of uniform section.
- **Abstract of cost** (quantity × rate) + **contingencies 3–5%** + **work-charged establishment 1.5–2%** (chowkidars, work munshis). **Centage charges** (departmental establishment, T&P, audit) ≈ **10–15%**, varying by department.
- **Specifications**: **general (brief)** = class of work and materials (with preliminary estimates); **detailed** = materials, proportions, workmanship, method, tests, mode of measurement (part of contract).
- **Schedule of Rates (SoR)**: e.g. **CPWD DSR** (Delhi Schedule of Rates), state SoRs; revised periodically and adjusted by a **cost index**. **DAR** = Delhi Analysis of Rates.
- **Measurement Book (MB)** = **most important original record** and **basis of all payments** (RA bills, final bill); machine-numbered pages; entries in **ink**, no erasures (score through and initial).
- **Muster roll** = the record of daily labour attendance and wages (departmental labour).
- **Rate of an item** = cost of **materials + labour + T&P/sundries + water charges + contractor's profit & overheads**. Analyse for a convenient unit (e.g. 10 m^3 or 1 m^3), then work out the rate per unit.
- **Contractor's profit = 10%** (classical textbook value). **Water charges = 1.5%** (Dutta). The CPWD analysis takes **1% water charges** and **15% contractor's profit & overheads**. In an MCQ, follow the options given.
- **Factors affecting rates**: specification, location (lead and lift), quantity of work, labour rates, materials, season, and the contractor's profit.
- **Lead** = horizontal haul distance. **Lift** = vertical height. In CPWD earthwork rates the basic **lead is 50 m and lift is 1.5 m**.

Material data	Standard value
Cement per bag	**50 kg** = **0.0347 m^3** (≈ 34.7 L; bulk density **1440 kg/m^3**)
Bags of cement per m^3	**1440/50 = 28.8 bags** (often rounded to ≈ 29; some texts use 30)
Dry volume of concrete	Wet volume × **1.52–1.57** (1.54 is common)
Dry volume of mortar	Wet volume × **~1.27–1.33**
Cement in 1 m^3 of 1:2:4 concrete	1.54/7 = 0.22 m^3 ≈ **6.3–6.4 bags**
Cement in 1 m^3 of 1:1.5:3 concrete	1.54/5.5 = 0.28 m^3 ≈ **8 bags**

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Modular bricks per m^3 of brickwork	**500** (19 × 9 × 9 cm; 20 × 10 × 10 cm with 10 mm mortar)
Mortar per m^3 of brickwork	**~0.25 m^3 wet**, or **~0.30 m^3 dry**. For 1:6 mortar this is ≈ 1.25 bags of cement.
Weight of steel bar	**D^2/162 kg/m** (D in mm; density 7850 kg/m^3)
Bar weights	8 mm 0.395; 10 mm 0.617; 12 mm 0.888; 16 mm 1.58; 20 mm 2.47; 25 mm 3.85 kg/m

- **IS 1200** = method of measurement of building & civil engineering works (in parts).
- **Accuracy**: dimensions to the nearest **0.01 m**, areas to the nearest **0.01 m^2**, volumes to the nearest **0.01 m^3**. Weights are recorded to the nearest **0.001 t (1 kg)** as specified.
- Work is measured **net, as fixed in place**, unless stated otherwise. Work in **foundation, plinth and superstructure** is measured separately.

Item	Unit
Earthwork in excavation / filling	**m^3**
Site clearance, surface dressing, jungle clearance	**m^2**
PCC, RCC, stone masonry	**m^3**
Reinforcement / structural steel	**kg** (or quintal / tonne)
Formwork (centring & shuttering)	**m^2** (area in contact with concrete)
Brickwork (one brick and above)	**m^3**
Half-brick wall (partition), honeycomb brickwork	**m^2**
Plastering, pointing, white/colour washing, painting, flooring, DPC	**m^2**
Door/window shutters, glazing	**m^2**
Wooden frames (chowkhats), timber	**m^3**
Pipes, rainwater pipes, railings, skirting/coping (when specified by length)	**running metre (m)**
Roofing sheets (GI / AC / profiled)	**m^2**

Deduction rule (IS 1200)	Rule
Brickwork (Part 3)	No deduction for openings up to **0.1 m^2**. No deduction for ends of beams, joists and posts up to **0.1 m^2** in section, or for the bearing of floor and roof slabs. Larger openings and RCC members are deducted.
Plastering (Part 12), openings ≤ **0.5 m^2**	**No deduction**, and nothing added for jambs, soffits or sills
Plastering, openings > 0.5 m^2 and ≤ **3 m^2**	Deduct for **one face only**, and nothing added for jambs, soffits or sills
Plastering, openings > **3 m^2**	Deduct for **both faces**, and **add** jambs, soffits and sills
Painting doors and windows	Flat area × **multiplying coefficient** (panelled, glazed, flush and so on; Part 15)

MEMORY TRICK

"**Brick 0.1, Plaster 0.5, Three for both.**" Brickwork ignores holes up to 0.1 m^2. Plaster ignores holes up to 0.5 m^2, deducts one face up to 3 m^2, and deducts both faces above 3 m^2. Steel: **D^2/162**. Cement: **1440 ÷ 50 = 28.8**.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Unit of measurement of half-brick partition wall? → **m^2**.
- Volume of one bag of cement? → **0.0347 m^3**.
- Weight of a 16 mm bar per metre? → **≈ 1.58 kg** (256/162).
- Number of modular bricks in 1 m^3 of brickwork? → **500**.
- Approximate estimate preferred for multi-storey buildings? → **Cubic content method**.
- Usual provision for contingencies? → **3–5%**.

12.7 Valuation ★★☆

- **Cost** = the actual expenditure incurred on construction or production (it relates to the **past**).
- **Price** = the amount asked or paid in an exchange.
- **Value** = the worth or utility of a property at the **present time**. It depends on demand, utility and income.
- Value may be more or less than cost. A property has **value only if it has utility**.

Term	Meaning
Market value	The price the property fetches in the open market at a given time. It fluctuates.
Book value	Original cost − total depreciation to date, as shown in the account books
Scrap value	Value of the **dismantled** materials at the end of life (e.g. of a building or machine)
Salvage value	Value at the end of useful life **without dismantling** (sold for use elsewhere)
Distress value	Value in a forced (distress) sale. It is less than market value.
Sentimental / accommodation / speculative value	Value above market value, arising from attachment, personal need or expected gain
Sinking fund	A fund built by periodic deposits to **replace** the property at the end of its life
Obsolescence	Loss of value because the design, function or style is out of date, even though the property is physically sound

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Freehold	Absolute ownership of land and building forever
Leasehold	The right to use for a fixed period (e.g. 99 years) on payment of rent to the lessor (owner). The lessee is the tenant.
Easement	A right enjoyed over another's land, such as a right of way, light or air

KEY FORMULAE

- **Straight-line depreciation**: D = (C − S)/n per year. The amount is the same every year.
- **Constant percentage (declining balance)**: $S = C(1 - p)^n$, so $p = 1 - (S/C)^{1/n}$. Depreciation is higher in the early years.
- **Sinking fund** annual instalment: $I = S \cdot i/[(1 + i)^n - 1]$. Sinking-fund coefficient = $i/[(1 + i)^n - 1]$.
- **Year's Purchase (YP)** for perpetual income: **YP = 1/i = 100/rate %** (e.g. 5% → 20)
- YP for a limited period (with a sinking fund): $YP = 1/(i + i_s)$, where i_s = sinking-fund coefficient
- **Capitalised value** = Net annual income × YP
- Net income = Gross income − outgoings (taxes, repairs, insurance, management, sinking fund)

- **Quantity survey method** of depreciation: depreciation is assessed from the actual physical condition (wear and tear) of each part of the property. It is common for valuing old buildings.
- **Rent fixation**: annual rent = interest on capital (land + building) at the expected rate + sinking fund + **outgoings** (repairs, municipal taxes, insurance, management). Annual repairs are often taken as ≈ 1/12 of gross rent (textbook practice).
- **Methods of valuation of buildings**: rental (income capitalisation), direct comparison (with sale of similar property), land & building (depreciation) method, profit method, development method.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Year's purchase for perpetual income at 5%? → **20**.
- Value of dismantled material of a building? → **Scrap value**.
- Depreciation method giving equal annual depreciation? → **Straight-line**.
- Capitalised value = ? → **Net annual income × YP**.
- Loss of value due to outdated design? → **Obsolescence**.

12.8 Contracts, Tendering & Public Procurement ★★★

- **Indian Contract Act, 1872**: Sec 2(a) **proposal (offer)**; 2(b) **acceptance** (accepted proposal = **promise**); 2(d) **consideration**; 2(e) agreement; 2(h) **contract = agreement enforceable by law**.
- **Valid contract** (Sec 10): **free consent** (no coercion, undue influence, fraud, misrepresentation, mistake), **competent parties** (Sec 11: age **18**, sound mind), **lawful consideration and object**, not declared void.
- **Void** = not enforceable; **voidable** = enforceable at the option of one party. Sec 56 = frustration; Sec 73 = compensation for breach; Sec 74 = **liquidated damages** (reasonable compensation up to the named sum).

Contract type	Key feature
Lump-sum	A fixed total sum for the whole work as per complete drawings and specifications. Extra items are paid from a schedule of rates. The contractor bears quantity risk.
Item rate (unit rate / schedule)	The contractor quotes a rate for each item. Payment = measured quantity × rate. It is the **most common in PWDs**.
Percentage rate	The contractor quotes a **% above/below the estimated cost** (based on SoR). Widely used by CPWD.
Cost plus percentage	Actual cost + an agreed % as profit. There is **no incentive to economise** (the higher the cost, the higher the profit).
Cost plus fixed fee	Actual cost + a fixed fee. The fee does not rise with cost, which is better for the owner.
Cost plus variable fee / target cost	The fee varies with performance against a target cost (incentive contract).
Labour contract	The department supplies materials. The contractor supplies only labour.
Piece-work	Small works at agreed rates without a formal tender or agreement
EPC (Engineering, Procurement & Construction)	A single contractor handles design and construction at a **fixed lump-sum price and time**. Most risk is on the contractor. Used by NHAI, railways and others.
Turnkey	The contractor designs, builds and commissions the facility, and the owner simply "turns the key"
BOT / BOOT / BOO	Build-Operate-Transfer / Build-Own-Operate-Transfer / Build-Own-Operate. The private party finances the project and recovers costs from tolls or user fees during the concession, then transfers the asset (except in BOO).
HAM (Hybrid Annuity Model)	Introduced by NHAI in 2016. The **government pays 40%** of the project cost during construction, and the developer arranges 60%. The developer is repaid through **annuities** with interest. **Toll is collected by the government**, so the developer bears no traffic risk.

- **Tender process**: **NIT** (name of work, estimated cost, EMD, tender fee, completion time, eligibility, dates) → sale/download → pre-bid meeting → submission & opening → evaluation (comparative statement) → acceptance of lowest evaluated bid (**L1**) → agreement.

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- **Two-bid (two-envelope) system**: the technical bid (eligibility and qualification) is opened first. The **financial bid is opened only for technically qualified bidders**.
- **Two-stage bidding** is used for complex or turnkey works where the specifications are finalised after the first stage.
- **EMD (Earnest Money Deposit / bid security)** is ≈ **2%** of the estimated cost put to tender (CPWD practice). It is forfeited if the bidder withdraws or does not sign. Under **GFR Rule 170** bid security is **2–5%**, and a **Bid Security Declaration** may be accepted instead.
- **Performance guarantee / performance security**: CPWD takes **5%** of the tendered value (reduced to 3% temporarily during 2020–23). Under **GFR Rule 171** (goods/services) it is **3–5%** of contract value (DoE OM 29 Dec 2023; originally 5–10%), valid 60 days beyond all contractual obligations, including the warranty period.
- **Security deposit**: CPWD recovers **2.5%** of the gross amount from running bills. The classical textbook figure is **10% of contract value including EMD** (often quoted as ~5%). Follow the options in the MCQ.
- **e-Procurement**: all tenders must be published on **CPPP (eprocure.gov.in)**. **GeM (Government e-Marketplace, 2016)** is **mandatory for common-use goods and services** available on it (GFR Rule 149).

GFR 2017 threshold (goods)	Original	Revised (DoE OM, July 2024)
Purchase without quotation (Rule 154)	Up to ₹25,000	**Up to ₹50,000**
Purchase by purchase committee (Rule 155)	₹25,000 – 2.5 lakh	**₹50,000 – 5 lakh**
Limited Tender Enquiry (Rule 162)	Up to ₹25 lakh	**Up to ₹50 lakh**
Advertised (open) Tender Enquiry (Rule 161)	₹25 lakh and above	**₹50 lakh and above**
GeM direct purchase (Rule 149)	Up to ₹25,000	**Up to ₹50,000**
Works by ministry: limited tender (Rule 139)	Below ₹5 lakh	**Below ₹10 lakh** (open tender ₹10–60 lakh)

- **Single-tender enquiry** (single source) is used only for proprietary items, emergencies or standardisation, with recorded reasons.
- **Global tender** is used where Indian sources are inadequate.
- **CPWD Works Manual** (latest edition 2022; earlier editions 2019, 2014) gives the procedures for CPWD works. The **General Conditions of Contract (GCC)** contain the standard clauses.

Contract clause / term	Key point
Defect Liability Period (DLP)	The period after completion (commonly **12 months**) during which the contractor rectifies defects at his own cost. The security deposit is released after it.
Liquidated damages (LD)	A pre-estimated compensation for delay. In CPWD (Clause 2) it is **1.5% per month** of delay, with a ceiling of **10% of the tendered value**.
Escalation / price variation clause	Compensates for changes in the price of materials and labour through indices. In CPWD it is **Clause 10CC**, for long-duration contracts (traditionally > 18 months). **Clause 10C** covers statutory wage increases.
Mobilisation advance	An advance to start the work. In CPWD it is up to **10%** of the tendered value, interest-bearing (10% simple interest), against a bank guarantee.
Secured advance	An advance against non-perishable materials brought to site, up to **75%** of their value (CPWD Clause 10B)
Extra / substituted items	Paid at derived rates from the agreement or SoR, or at market rates
Force majeure	Events beyond control (war, flood, epidemic). Time is extended and no LD is charged.

- **Arbitration and Conciliation Act, 1996**: based on **UNCITRAL Model Law (1985)**; amended 2015, 2019, 2021. Agreement **in writing** (Sec 7); **odd** number of arbitrators, else sole (Sec 10); award within **12 months** of completion of pleadings, +6 months by consent (Sec 29A); fast track **6 months** (Sec 29B); setting aside under **Sec 34** within **3 months** (+30 days); Part III = **conciliation**.
- **FIDIC** (founded 1913, HQ **Geneva**) Rainbow Suite: **Red** = construction, employer's design (measured); **Yellow** = plant & design-build; **Silver** = **EPC/turnkey**; **Green** = short form; **White** = client–consultant; Pink = MDB edition; Gold = DBO. Disputes → **DAAB** (2017 editions).

CODE UPDATE

The **Department of Expenditure OM of 10 July 2024** amended GFR 2017 and roughly doubled the monetary limits (₹25,000 → ₹50,000; LTE ₹25 lakh → ₹50 lakh). Older question banks still quote the 2017 figures, so check the options for both. The **Mediation Act, 2023** now provides for pre-litigation mediation.

MEMORY TRICK

FIDIC colours: "**R**ed = **R**e-measured; **Y**ellow = **Y**ou (the contractor) design; **S**ilver = **S**ingle-point EPC; **G**reen = **G**entle (short form)."

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PREVIOUSLY ASKED / LIKELY QUESTIONS

- Contract with no incentive for the contractor to economise? → **Cost plus percentage**.
- Most common contract in PWD works? → **Item rate**.
- Usual EMD in CPWD tenders? → **≈ 2%** of the estimated cost.
- Contract = agreement + ? → **Enforceability by law** (Sec 2(h)).
- FIDIC book for EPC/turnkey projects? → **Silver Book**.
- In HAM, who collects toll? → **The government (NHAI)**.

12.9 Construction Equipment, Quality & Safety ★★☆

Equipment	Use / key point
Bulldozer (crawler/wheel tractor + blade)	Clearing, pushing and spreading earth over **short haul, up to ~100 m**. Angle dozer, tilt dozer.
Scraper	**Loads, hauls and dumps** in thin layers. Economical over medium haul, roughly 100 m to over 1 km (motorised types for longer haul).
Power shovel (front shovel)	Digs **above its track level** (upward digging). Works in **hard soil** and loads trucks.
Dragline	Digs **below its level** in **soft, wet or marshy** soil. It has the **longest reach** but is less precise. Used for canals, ponds and river beds.
Backhoe (hoe)	Digs **below its level** with good control and force. Used for **trenches** and foundations.
Clamshell	Digs **vertically** in a confined space: cofferdams, wells, shafts, and loading loose material from stockpiles.
Loader (front-end)	Loads loose material into trucks
Motor grader	Levelling, shaping, **camber**, ditch cutting and finishing
Trenchers, rippers	Continuous trenches / loosening hard soil and soft rock

Roller / compactor	Best soil
Smooth-wheeled (static)	Granular bases, WBM and **bituminous finishing** (gives a smooth surface)
Sheepsfoot	**Cohesive soils (clay)**. Compacts from the bottom upward by kneading/tamping.
Pneumatic-tyred	Wide range: silty/sandy soils and bituminous layers (kneading action)
Vibratory	**Granular soils** (sand, gravel)
Plate compactor / rammer (tamper)	Confined areas, trenches, behind walls

- **Hoisting**: **tower crane** (high-rise), **mobile crane** (truck/crawler), **derricks** (guy, stiff-leg), gantry cranes, hoists, winches.
- **Concrete equipment**: mixers (tilting, non-tilting, reversing drum; "**10/7 mixer**" = 10 cft dry materials → 7 cft mixed concrete per batch), transit mixers, batching plants, pumps, vibrators (**needle/immersion** most common, surface/screed, form, table).
- **Output of excavators**: Q = (3600/cycle time in s) × bucket capacity × fill factor × job efficiency × swell correction. A typical job efficiency is a **50-minute hour**, i.e. 0.83.
- **Swell (bulking)**: loose volume > bank volume > compacted volume.
- **Equipment cost** = **owning (fixed)**: depreciation, interest, insurance, taxes, storage + **operating**: fuel, lubricants, operator wages, repairs, tyres.
- Depreciation methods for equipment are straight-line, declining balance, sum-of-years-digits and sinking fund.
- **Hire vs buy**: buy when utilisation is high and long-term. Hire for short or occasional use.
- **Economic life** = the age at which the average cost per hour (owning + operating) is minimum.

Quality concept	Key fact
QC vs QA	QC = **inspection and testing of the product** (detects defects). QA = **planned systematic process** that prevents defects (process-oriented).
ISO 9001:2015	Quality Management System standard (amendment 2024 adds climate change). Related standards: ISO 14001 (environment), **ISO 45001:2018** (occupational health & safety).
TQM	Organisation-wide continuous improvement and customer focus. Key names: **Deming** (PDCA cycle, 14 points), **Juran** (quality trilogy), **Crosby** (zero defects), **Ishikawa** (fishbone / cause-and-effect diagram).
Six Sigma	**3.4 defects per million opportunities**. Method **DMAIC** (Define, Measure, Analyse, Improve, Control). Started at Motorola (1986).
Kaizen / Pareto	Kaizen = small continuous improvement. Pareto = the **80/20 rule**.
Value engineering	**L.D. Miles** (General Electric, 1940s). **Value = Function/Cost**. Aim: get the required function at the lowest life-cycle cost without lowering quality. Tool: the FAST diagram.
Lean construction	Eliminate waste and work on pull and just-in-time. Uses the **Last Planner System** (Ballard & Howell).
BIM (Building Information Modelling)	A shared digital model: 3D geometry, **4D = time**, **5D = cost**, 6D/7D = sustainability and facility management (the order varies by source). It detects clashes before construction.

- **Safety**: **BOCW (RE&CS) Act, 1996** applies to establishments with **10 or more** building workers; **BOCW Welfare Cess Act, 1996** cess **1–2% of construction cost** (1% notified); **NBC 2016 Part 7** = construction practices & safety; **IS 3696** = scaffolds and ladders; **PPE**: helmet (IS 2925), harness,

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safety shoes, gloves, goggles, reflective jacket; scaffolds need guard rails, toe boards, bracing and ties.

CODE UPDATE

The **Occupational Safety, Health & Working Conditions Code, 2020** subsumes the BOCW Act 1996, and the Code on Social Security, 2020 subsumes the Cess Act. The four Labour Codes were brought into force from **21 November 2025**. Questions may still name the BOCW Act.

- **Warehouse / godown construction (CWC context) – good practice**:
  - **Plinth** well above **HFL** and ground, usually at **truck-bed (loading platform) height**, with covered platforms and ramps.
  - **Rodent-proofing**: smooth plinth face with projecting rat-proof course; steel-sheeted shutters without gaps; wire mesh on ventilators and drains.
  - **Floor**: rigid concrete over compacted sub-base with DPC/polythene membrane; VDF or trimix finish; designed for **stacking load** and **forklift/truck wheel loads**.
  - **Ventilation & fumigation**: ridge/turbo ventilators that can be closed; godown **airtight when closed** for fumigation; damp-proof walls and leak-proof roof.
  - **PEB**: tapered built-up frames, cold-formed Z/C purlins and girts, metal sheeting; large clear spans, fast erection (IS 800:2007; wind IS 875 Part 3:2015).
  - **CAP (Cover and Plinth)** = temporary open storage of food grains on a raised plinth with wooden crates/dunnage, covered with polythene. **Steel silos** for bulk grain.
  - **Fire safety** (NBC Part 4): hydrants, extinguishers, compartment separation, fire-tender access.

PREVIOUSLY ASKED / LIKELY QUESTIONS

- Equipment for excavation below its own level in soft, wet soil with long reach? → **Dragline**.
- Roller best for clayey soil? → **Sheepsfoot roller**.
- Equipment that excavates above track level? → **Power (front) shovel**.
- Six Sigma corresponds to how many defects per million? → **3.4**.
- Value in value engineering = ? → **Function/Cost**.
- 4D BIM adds? → **Time (schedule)**.

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13. Last-Day Revision (Formula & Value Sheet)

Topic	Must-remember facts
Elastic constants	E = 2G(1 + ν) = 3K(1 − 2ν); E = 9KG/(3K + G); ν: 0 to 0.5 (0.5 = incompressible); steel E = **2 × 10⁵ N/mm²**, ν = **0.3**; α steel = 12 × 10⁻⁶ /°C
Beam BM/deflection	SS + UDL: M = **wL²/8**, δ = **5wL⁴/384EI**; SS + central P: PL/4, PL³/48EI; cantilever + P: PL, PL³/3EI; cantilever + UDL: wL²/2, wL⁴/8EI; fixed + UDL: wL²/12 (ends), wL²/24 (centre), wL⁴/384EI
Shear stress ratio τmax/τavg	Rectangle **1.5**; circle **4/3**; triangle 1.5 (at h/2); thin ring 2
Euler columns	P = π²EI/Le²; Le: both hinged L; both fixed **L/2**; fixed–hinged **L/√2**; fixed–free **2L**
Torsion & shells	T/J = τ/r = Gθ/L; P = 2πNT/60; thin cylinder hoop σ = pd/2t, longitudinal pd/4t; sphere pd/4t
Shape factor	Rectangle 1.5; circle 1.7; I-section 1.12–1.15; diamond 2.0; triangle 2.34
Indeterminacy	Plane truss m + r − 2j; plane frame 3m + r − 3j; perfect truss m = 2j − 3; MDM carry-over ½ (far end fixed), stiffness 4EI/L (far end fixed), 3EI/L (far end hinged)
IS 456 key values	Min grade RCC **M20**; Ec = 5000√fck; fcr = 0.7√fck; γm 1.5 / 1.15; xu,max/d 0.53 / **0.48** / 0.46 (Fe250/415/500); Mu,lim = 0.148 / **0.138** / 0.133 fck bd²; covers: mild 20, moderate 30, severe 45, very severe 50, extreme 75 mm; L/d basic 7 / 20 / 26
IS 456 detailing	Min steel beam 0.85bd/fy; max 4% bD; slab 0.12% (HYSD); column 0.8–4% (6% max), min 4 bars rect, 6 circular, 12 mm dia; min eccentricity L/500 + D/30 ≥ 20 mm; short column Le/D < 12; Pu = 0.4fck Ac + 0.67fy Asc; stirrup spacing ≤ 0.75d or 300 mm; deflection span/250
IS 800	γm0 1.10, γm1 1.25; bolt γmb 1.25; weld 1.25 shop / 1.5 field; throat = 0.7 × size; min pitch 2.5d; max λ: compression (DL + LL) 180, tension members (other than pre-tensioned) 400; buckling α: a 0.21, b 0.34, c 0.49, d 0.76
Cement & concrete	C3S early strength, C2S later strength, C3A flash set (max heat); IST ≥ **30 min**, FST ≤ **600 min**; Le Chatelier ≤ 10 mm; fine aggregate < 4.75 mm; f'ck = fck + 1.65S; cylinder ≈ 0.8 × cube; PSC min grade M40 (pre-tensioned), M30 (post-tensioned)
Workability (slump)	IS 456: very low (pavements) – judged by compaction factor 0.75–0.80; low 25–75 mm; medium 50–100 mm (heavily reinforced); high 100–150 mm (trench fill, in-situ piling); tremie very high (flow test); Vee-Bee suits stiff mixes
Soil phase relations	Se = wG; n = e/(1 + e); γd = γ/(1 + w); γd = Gγw/(1 + e); ic = (G − 1)/(1 + e) ≈ 1; Cu > 4 (gravel) / > 6 (sand), Cc 1–3 well graded; A-line PI = 0.73(LL − 20)
Consolidation & shear	Cc = 0.009(LL − 10); Tv(50%) = 0.197, Tv(90%) = 0.848; Tv = Cv t/d²; qu = 2c (φ = 0); Boussinesq σz = 0.4775Q/z² on the axis; Rankine Ka = (1 − sin φ)/(1 + sin φ)
Bearing capacity	Terzaghi strip: cNc + qNq + 0.5γBNγ; square 1.3cNc + qNq + 0.4γBNγ; circular 1.3cNc + qNq + 0.3γBNγ; Rankine min depth = (q/γ)[(1 − sin φ)/(1 + sin φ)]²; well tilt 1 in 80, shift 150 mm
Fluid statics	1 atm = 101.325 kPa = 10.3 m water = 760 mm Hg; centre of pressure h̄ + IG/(A h̄); stable floating if GM > 0; capillary rise h = 4σ cos θ/(ρ g d)
Flow measurement	Cc 0.64, Cv 0.97–0.98, Cd 0.62 (orifice); venturi Cd 0.95–0.99; orificemeter 0.6–0.65; rectangular notch ∝ $H^{3/2}$, V-notch ∝ $H^{5/2}$; % error in Q = 1.5 × or 2.5 × % error in H
Pipe flow	Re < 2000 laminar; f = 64/Re; Vmax = 2Vavg; hf = fLV²/2gD; sudden expansion $(V_1 - V_2)^2/2g$; entry 0.5V²/2g; exit V²/2g; max power when hf = H/3 (η = 66.7%); water hammer ΔP = ρcV, critical time 2L/c
Open channel	Manning V = (1/n)$R^{2/3}S^{1/2}$; best rectangle b = 2y, R = y/2; trapezoid = half hexagon; yc = $(q^2/g)^{1/3}$, Ec = 1.5yc; jump loss $(y_2 - y_1)^3/4y_1y_2$; Froude model: V ∝ $Lr^{1/2}$, Q ∝ $Lr^{5/2}$
Hydrology & irrigation	Rational Q = CIA/3.6 (A km², I mm/h); Δ = 8.64B/D; Lacey f = 1.76√d_{mm}, P = 4.75√Q; Kennedy V_o = 0.55m$D^{0.64}$; Bligh creep; Khosla exit gradient; gravity dam no tension → resultant in middle third; risk = 1 − $(1 - 1/T)^n$
Water supply	135 lpcd (with sewerage); design period 30 yr; IS 10500: pH 6.5–8.5, TDS 500/2000, fluoride 1.0/1.5, nitrate 45, arsenic 0.01, hardness 200/600 mg/L; residual chlorine ≥ 0.2 mg/L; slow sand filter 100–200 L/h/m² vs rapid sand 3000–6000 L/h/m² (≈ 30× faster); HOCl dominant at low pH
Sewage & air	Self-cleansing velocity 0.6–0.9 m/s; BOD_5/BODu ≈ 0.68; DO sat. ≈ 9.1 mg/L at 20 °C; SVI 50–150 good; septic tank detention 24 h; effluent BOD ≤ 30, TSS ≤ 100 mg/L (inland surface water); DALR 9.8 °C/km; acid rain pH < 5.6; AQI 0–50 good, 401–500 severe
MSW & noise	SWM Rules 2016; compost C/N 25–30; landfill gas CH_4 ≈ 50–60%; BMW yellow/red/white/blue; noise day/night dB(A): industrial 75/70, commercial 65/55, residential 55/45, silence 50/40; two equal sources = +3 dB; day 6 am–10 pm

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Highways	SSD = $vt + v^2/2gf$ (t = 2.5 s); $e + f = V^2/127R$ (f = 0.15); e max 7% (plains), 10% (hills); extra widening $nl^2/2R + V/(9.5\sqrt{R})$; shift $L^2/24R$; C = 80/(75 + V); Nagpur plan 1943; IRC 1934; IRC 37:2018 flexible, IRC 58:2015 rigid; CBR loads 1370/2055 kg at 2.5/5.0 mm
Traffic	q = kv; qmax = vf kj/4; time-mean speed ≥ space-mean speed; 85th percentile → speed limit; 98th → design speed; Webster $C_o = (1.5L + 5)/(1 - Y)$; STOP sign octagon; mandatory signs circular, warning triangular, informatory rectangular
Railway & airport	BG 1676, MG 1000, NG 762 mm; coning 1 in 20; runway length corrections: +7% per 300 m elevation, +1% per °C above standard temperature, +20% per 1% effective gradient
Surveying	Curvature $0.0785d^2$, refraction $0.0112d^2$, combined $0.0673d^2$ (d in km, m); ΣBS − ΣFS = last RL − first RL; FB − BB = 180°; Bowditch: equal angular & linear precision; R = 1719/D (30 m arc); T = R tan(Δ/2); Rankine δ = 1718.9c/R min; stadia K = 100, C = 0; sag correction $l^3w^2/24P^2$
GPS / GIS	GPS 24+ satellites, 6 orbital planes, ~20,200 km, ~12 h; min 4 satellites for 3D fix; NavIC 7 satellites; raster = cells, vector = point/line/polygon; photo scale = f/(H − h); overlap 60% forward, 30% side
Project management	te = (to + 4tm + tp)/6; σ = (tp − to)/6; Z = (Ts − Te)/σ; TF = LS − ES; FF = ES_{succ} − EF; critical path TF = 0; cost slope = (Cc − Cn)/(Tn − Tc); PERT event-oriented & probabilistic, CPM activity-oriented & deterministic
Estimating	Cement 1 bag = 50 kg ≈ 0.0347 m^3; steel kg/m = $D^2/162$; dry volume of concrete ≈ 1.54 × wet; contingencies 3–5%; work-charged establishment 1.5–2%; contractor's profit 10%; YP (perpetual) = 100/i

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14. 500 Most Expected Questions & Answers

> **NOTE**
> Rapid-fire revision: 500 one-line questions chosen for the CWC AM (Civil) paper, in the same order as the chapters. Cover the answer, attempt, then check. Numericals carry a short working hint.

14.1 Engineering Mechanics & Strength of Materials (Q 1–55)

1. Lami's theorem states that each of three forces in equilibrium is proportional to? → **Sine of the angle between the other two forces**
2. Two equal forces P act at a point at 60° to each other. Resultant? → **√3 P ≈ 1.732P (2P cos 30°)**
3. The principle of transmissibility of forces is valid for? → **Rigid bodies only (external effects)**
4. A body in equilibrium under three non-parallel coplanar forces: their lines of action must be? → **Concurrent (meet at one point)**
5. Number of reaction components at a fixed support in a plane structure? → **3 (H, V and moment)**
6. Coefficient of friction μ is equal to? → **tan φ (φ = angle of friction)**
7. A block on a plane inclined at 30° is just on the point of sliding. μ? → **0.577 (tan 30°)**
8. Ratio of belt tensions on the tight and slack sides, T_1/T_2? → **$e^{\mu\theta}$ (θ in radians)**
9. Centroid of a triangular area from its base (height h)? → **h/3**
10. Centroid of a semicircular area from its diameter? → **4r/(3π) ≈ 0.424r**
11. Centroid of a solid right circular cone from its base? → **h/4**
12. Moment of inertia of a rectangle b × d about its base? → **$bd^3/3$**
13. MI of a circular section of diameter 100 mm about a diameter? → **≈ 4.91×10^6 mm⁴ ($\pi d^4/64$)**
14. Polar moment of inertia of a solid circular section of diameter d? → **$\pi d^4/32$**
15. Product of inertia of an area is zero when? → **Either axis is an axis of symmetry**
16. Radius of gyration of a rectangle about its centroidal axis parallel to width b? → **d/√12 ≈ 0.289d**
17. A plane truss has 7 joints. Members needed for a perfect frame? → **11 (2j − 3)**
18. A projectile is fired at 20 m/s at 45°. Horizontal range (g = 9.81)? → **≈ 40.8 m (u^2/g)**
19. Reaction on a person in a lift moving up with acceleration a? → **m(g + a)**
20. Coefficient of restitution for a perfectly elastic collision? → **1 (kinetic energy conserved)**
21. In which type of collision is linear momentum conserved? → **All collisions (elastic and inelastic)**
22. Law of machine P = mW + C. Maximum mechanical advantage? → **1/m**
23. A machine is self-locking (irreversible) when its efficiency is? → **Less than 50%**
24. Hooke's law holds up to? → **Limit of proportionality**
25. Relation between E, G and Poisson's ratio ν? → **E = 2G(1 + ν)**
26. Relation between E, K and ν? → **E = 3K(1 − 2ν)**
27. Steel bar 2 m long, area 100 mm², pulled by 20 kN (E = 2 × 10^5 N/mm²). Elongation? → **2 mm (PL/AE)**
28. Fully restrained steel bar heated by 50°C (α = 12 × 10^{-6}/°C, E = 2 × 10^5 MPa). Stress? → **120 N/mm² (EαΔT)**
29. Modulus of resilience is? → **$\sigma_e^2/2E$ (strain energy per unit volume at elastic limit)**
30. 0.2% proof stress is used for materials that? → **Have no well-defined yield point**
31. Under a uniformly varying load, SFD and BMD shapes are? → **SFD parabolic (2nd degree), BMD cubic (3rd degree)**
32. Rate of change of bending moment along a beam, dM/dx, equals? → **Shear force**
33. SS beam of span 4 m with central point load 20 kN. Maximum BM? → **20 kN·m (WL/4)**
34. Cantilever 3 m long with UDL 10 kN/m. Maximum BM? → **45 kN·m ($wL^2/2$, at fixed end)**
35. SS beam with two equal loads at the third points: the middle third is under? → **Pure bending (SF = 0)**
36. Points of contraflexure never occur under gravity loads in? → **Simply supported beams and cantilevers**
37. In elastic bending the neutral axis passes through the? → **Centroid of the section**
38. Beam 100 mm wide, 200 mm deep, BM 10 kN·m. Maximum bending stress? → **15 N/mm² (M/Z, Z = $bd^2/6$)**
39. Stiffest rectangular beam cut from a round log: depth/width ratio? → **√3**

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40. τ_{max}/τ_{avg} for a thin-walled circular tube? → **2.0**

41. In an I-section beam most of the shear force is resisted by the? → **Web**

42. Maximum deflection of an SS beam with full-span UDL? → **$5wL^4/384EI$**

43. Maximum deflection of a cantilever with point load W at its free end? → **$WL^3/3EI$**

44. A free end of the real beam becomes, in the conjugate beam? → **Fixed end**

45. Span of an SS beam with UDL (w per m) is doubled. Deflection becomes? → **16 times ($\propto L^4$)**

46. Shaft at 300 rpm transmits torque 1 kN·m. Power? → **≈ 31.4 kW ($2\pi NT/60$)**

47. Diameter of a solid shaft is doubled. Torque capacity becomes? → **8 times ($\propto d^3$)**

48. Euler's crippling load for a column? → **$P_e = \pi^2 EI/L_e^2$**

49. Rankine–Gordon formula is applicable to columns of? → **All lengths (short and long)**

50. Bar under uniaxial stress 100 MPa. Maximum shear stress? → **50 MPa ($\sigma/2$, on 45° plane)**

51. Theory of failure suitable for brittle materials? → **Maximum principal stress theory (Rankine)**

52. Shear yield stress by von Mises theory? → **$f_y/\sqrt{3} \approx 0.577\ f_y$**

53. Thin cylinder: d = 1000 mm, t = 10 mm, p = 2 N/mm². Hoop stress? → **100 N/mm² ($pd/2t$)**

54. Theory used for stresses in thick cylinders? → **Lamé's theory**

55. Stiffness of two equal springs (k each) connected in parallel? → **2k**

14.2 Structural Analysis & Engineering Materials (Q 56–100)

56. Degree of static indeterminacy of a propped cantilever? → **1**

57. Plane truss with 10 members, 6 joints and 3 reactions. D_s? → **1 ($m + r - 2j = 10 + 3 - 12$)**

58. Continuous beam of 4 spans (one hinge, rest rollers), general loading. D_s? → **3 (6 reactions − 3)**

59. Static indeterminacy of a two-hinged arch? → **1 (horizontal thrust H is redundant)**

60. Stresses due to temperature change and support settlement occur only in? → **Statically indeterminate structures**

61. By Castigliano's theorem for deflections, the partial derivative of total strain energy with respect to a load P ($\partial U/\partial P$) equals? → **Deflection Δ at the point and in the direction of P**

62. Theorem of least work is also known as? → **Menabrea's theorem**

63. Maxwell's reciprocal theorem is a special case of? → **Betti's law**

64. Influence lines of statically indeterminate structures are? → **Curved lines**

65. SS beam of span 10 m: ILD ordinate for BM at a section 4 m from the left support? → **2.4 m ($ab/L = 4 \times 6/10$)**

66. Single rolling load 100 kN on an SS beam of span 8 m. Absolute maximum BM? → **200 kN·m ($WL/4$)**

67. Fixed beam of span 6 m with UDL 12 kN/m. Fixed-end moment? → **36 kN·m ($wL^2/12$)**

68. Fixed-end moment at the heavier end of a fixed beam with triangular load (0 to w)? → **$wL^2/20$ ($wL^2/30$ at the light end)**

69. Prop reaction of a propped cantilever with central point load W? → **5W/16**

70. Central support reaction of a two equal-span continuous beam with UDL? → **5wL/4**

71. Carry-over factor for a member whose far end is hinged? → **Zero**

72. Stiffness of a prismatic member with the far end fixed? → **4EI/L**

73. Joint with two members (same EI, far ends fixed) of lengths 4 m and 6 m. DF of the 4 m member? → **0.6 (EI/1.667EI)**

74. Primary unknowns in the flexibility (force) method? → **Redundant forces**

75. Bending moment in a parabolic three-hinged arch under full-span UDL? → **Zero everywhere (pure compression)**

76. Three-hinged parabolic arch, span 20 m, rise 4 m, UDL 10 kN/m. Horizontal thrust? → **125 kN ($wL^2/8h$)**

77. Shape of a cable hanging under its own weight? → **Catenary**

78. Number of plastic hinges needed for complete collapse? → **$D_s + 1$**

79. Collapse load of an SS beam with central point load? → **$4M_p/L$**

80. Shape factor of a triangular section (base horizontal)? → **2.34**

81. Nominal size of a modular brick including mortar joint? → **200 × 100 × 100 mm**

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82. Excess alumina in brick earth causes? → **Shrinkage, cracking and warping on drying**
83. Red colour of bricks is due to? → **Iron oxide**
84. Most common brick kiln in India? → **Bull's trench kiln**
85. Approximate number of modular bricks per m^3 of brickwork? → **About 500**
86. A brick cut lengthwise into two halves is called? → **Queen closer**
87. Minimum compressive strength of heavy-duty bricks (IS 2180)? → **40 N/mm²**
88. Granite is which type of rock? → **Igneous (plutonic)**
89. Slate is formed by metamorphism of? → **Shale**
90. Direction of the natural bed of stones in an arch? → **Radial (perpendicular to thrust)**
91. Lime containing 21–30% clay is called? → **Eminently hydraulic lime**
92. Bulking of sand is maximum at a moisture content of about? → **4–6%**
93. Moisture content of seasoned timber for furniture and joinery? → **About 10–12%**
94. Commonly used drier in oil paints? → **Litharge**
95. Main constituent of ordinary glass? → **Silica (about 70%)**
96. Toughened glass is made by? → **Heating, then rapid cooling**
97. PVC is an example of? → **Thermoplastic**
98. Hot-laid, voidless, impervious bituminous material used for DPC and flat roofs? → **Mastic asphalt**
99. Stair riser 15 cm. Tread by the rule 2R + T = 60 cm? → **30 cm**
100. Minimum area of a kitchen as per NBC 2016? → **5.0 m² (minimum width 1.8 m)**

14.3 Steel Structures & IS 800 (Q 101–130)

101. Main design method adopted in IS 800:2007? → **Limit State Method**
102. IS code for hot-rolled structural steel? → **IS 2062:2011**
103. Yield stress of E250 steel for plate thickness 20–40 mm? → **240 MPa**
104. Unit mass of steel as per IS 800? → **7850 kg/m³**
105. Partial safety factor γ_{m1} for resistance governed by ultimate stress? → **1.25**
106. Value of ε for steel with f_y = 350 MPa? → **0.845 (√(250/350))**
107. Section class that can form a plastic hinge with adequate rotation capacity? → **Class 1 (Plastic)**
108. Partial safety factor for DL and IL in the DL + IL combination (ULS)? → **1.5 each**
109. Ultimate and yield strength of a property class 4.6 bolt? → **400 MPa and 240 MPa**
110. Standard clearance hole diameter for a 16 mm bolt? → **18 mm**
111. Minimum pitch for 20 mm diameter bolts? → **50 mm (2.5d)**
112. Maximum pitch of bolts in tension members? → **16t or 200 mm, whichever is less**
113. Minimum edge distance for a rolled, machine-cut or planed edge? → **1.5 × hole diameter**
114. Net tensile stress area of a threaded bolt is about? → **0.78 × gross shank area**
115. Plate 200 × 10 mm with 2 bolts of 20 mm (holes 22 mm) in one row. Net area? → **1560 mm² ((200 − 2 × 22) × 10)**
116. Effective throat of an 8 mm fillet weld (fusion faces at 90°)? → **5.6 mm (0.7s)**
117. Fillet welds are permitted when the angle between fusion faces is? → **60° to 120°**
118. Minimum lap in a lap joint? → **4 × thinner plate thickness or 40 mm, whichever more**
119. Design strength of a shop fillet weld on E250 steel? → **≈ 189 MPa (410/(√3 × 1.25))**
120. Vertical impact allowance for a hand-operated crane gantry? → **10% of maximum static wheel load**
121. Gross area 1000 mm², f_y = 250 MPa. Design strength in gross-section yielding? → **≈ 227 kN ($A_g f_y$/1.10)**
122. Factor α in the preliminary net-section rupture formula for 3 bolts? → **0.7**
123. Maximum slenderness ratio for a beam compression flange against lateral torsional buckling? → **300**
124. IS 800 effective length of a column fixed at one end and hinged at the other? → **0.80 L**
125. Imperfection factor α for buckling class a? → **0.21**
126. For battened columns the effective slenderness is increased by? → **10%**
127. Rolled I-beam, h = 300 mm, t_w = 7.5 mm, f_y = 250 MPa. Design shear strength? → **≈ 295 kN ($ht_w f_y$/(√3 × 1.10))**
128. Deflection limit for a gantry girder carrying an EOT crane above 50 t? → **Span/1000**
129. Design wind pressure for V_z = 50 m/s? → **1500 N/m² ($0.6V_z^2$)**

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130. Truss with diagonals in compression and verticals in tension under gravity loads? → **Howe truss**

14.4 RCC Design & IS Codes (Q 131–175)

131. Partial safety factor for concrete at the limit state of collapse (IS 456)? → **1.5**

132. Design yield stress of reinforcing steel in LSM? → **0.87 f_y (f_y/1.15)**

133. Design peak stress of concrete in the LSM flexural stress block? → **0.446 f_{ck} (0.67 f_{ck}/1.5)**

134. Short-term modulus of elasticity of M30 concrete as per IS 456? → **≈ 27,386 N/mm² (5000√30)**

135. Partial load factor for DL + IL combination at limit state of collapse? → **1.5**

136. Nominal cover for "moderate" exposure (IS 456 Table 16)? → **30 mm**

137. Maximum free w/c ratio for RCC in "severe" exposure? → **0.45**

138. Maximum cement content (OPC, excluding fly ash/GGBS) permitted by IS 456? → **450 kg/m³**

139. Modular ratio expression in WSM (IS 456 Annex B)? → **$m = 280/(3\sigma_{cbc})$**

140. Modular ratio for M25 concrete (σ_{cbc} = 8.5 N/mm²)? → **10.98 (280/25.5)**

141. Permissible tensile stress in mild steel bars up to 20 mm dia (WSM)? → **140 N/mm²**

142. Maximum compressive strain in concrete under pure axial compression (LSM)? → **0.002**

143. Limiting $x_{u,max}/d$ for Fe 415 steel? → **0.48**

144. $M_{u,lim}$ of a beam 230 × 450 mm (effective), M20, Fe 415? → **≈ 128.5 kN·m ($0.138 f_{ck} bd^2$)**

145. Maximum area of tension reinforcement in a beam? → **0.04 bD (4% of gross area)**

146. Effective flange width of a monolithic L-beam? → **$l_0/12 + b_w + 3D_f$**

147. Maximum redistribution of moments permitted in LSM? → **30%**

148. Maximum clear distance between lateral restraints of a simply supported beam? → **60b or $250b^2/d$, whichever less**

149. A simply supported beam is a deep beam when l/D is less than? → **2.0**

150. $\tau_{c,max}$ for M25 concrete (LSM, Table 20)? → **3.1 N/mm²**

151. Minimum shear reinforcement condition (cl 26.5.1.6)? → **$A_{sv}/(b\ s_v) \geq 0.4/(0.87\ f_y)$**

152. V_u = 150 kN, b = 300 mm, d = 500 mm. Nominal shear stress? → **1.0 N/mm² (V_u/bd)**

153. Maximum share of total shear reinforcement that bent-up bars may provide? → **50% (half)**

154. Increase in design bond stress for deformed bars over plain bars? → **60%**

155. Development length of a 16 mm Fe 415 deformed bar in tension, M20? → **≈ 752 mm ($0.87 f_y \varphi/4\tau_{bd}$, ≈ 47φ)**

156. Anchorage value of a standard U-type hook? → **16φ**

157. Lap length of bars in flexural tension? → **L_d or 30φ, whichever greater**

158. Bars larger than what diameter should not be lapped (welded instead)? → **36 mm**

159. Equivalent moment due to torsion, M_t (cl 41.4.2)? → **$T_u(1 + D/b)/1.7$**

160. Basic span/effective depth ratio for a cantilever (span ≤ 10 m)? → **7**

161. Minimum effective depth (basic ratio only) for a 5 m simply supported beam? → **250 mm (5000/20)**

162. Maximum spacing of main bars in a slab? → **3d or 300 mm, whichever less**

163. Torsion reinforcement at corners of a two-way slab (both edges discontinuous)? → **¾ of maximum mid-span steel**

164. Minimum length of a drop in a flat slab, in each direction? → **One-third of panel length**

165. Recommended effective length of a column fixed at both ends (no sway)? → **0.65 l**

166. Minimum diameter of longitudinal bars in a column? → **12 mm**

167. Short column 400 × 400 mm, M20, A_{sc} = 1600 mm² Fe 415. Axial capacity P_u? → **≈ 1712 kN ($0.4 f_{ck} A_c + 0.67 f_y A_{sc}$)**

168. Minimum eccentricity for a column, l = 3 m, D = 450 mm? → **21 mm (l/500 + D/30)**

169. Strength of a helically reinforced column relative to a tied column? → **1.05 times**

170. Minimum nominal cover to reinforcement in footings? → **50 mm**

171. Minimum period before removing props to slabs spanning over 4.5 m (OPC)? → **14 days**

172. Permissible crack width in liquid-retaining RCC structures (IS 3370)? → **0.2 mm**

173. Minimum dimension of a column as per IS 13920:2016? → **300 mm**

174. Seismic zone factor Z for zone III (IS 1893:2016)? → **0.16**

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175. Z = 0.24, I = 1.0, R = 5, S_a/g = 2.5. Design horizontal coefficient A_h? → **0.06 ((Z/2)(I/R)(S_a/g))**

14.5 Concrete Technology & Prestressed Concrete (Q 176–220)

176. Bogue compound responsible for later strength with the lowest heat of hydration? → **C_2S (belite)**

177. Maximum MgO content permitted in OPC (IS 269)? → **6%**

178. Temperature in the burning (clinkering) zone of a rotary kiln? → **1400–1500 °C**

179. Approximate w/c ratio needed for complete hydration of cement? → **≈ 0.38 (bound 23% + gel water 15%)**

180. Maximum final setting time of OPC? → **600 minutes (10 h)**

181. Maximum expansion permitted in the Le Chatelier soundness test? → **10 mm**

182. Standard consistency: Vicat plunger penetration measured from the mould bottom? → **5–7 mm (33–35 mm from top)**

183. P = 28%. Water for a cement mortar cube (200 g cement + 600 g sand)? → **80 g ((P/4 + 3)% of 800 g)**

184. Volume of one 50 kg bag of cement (bulk density 1440 kg/m³)? → **0.0347 m³ (≈ 35 litres)**

185. Minimum 7-day compressive strength of 53 grade OPC? → **37 MPa**

186. Fly ash content permitted in PPC (IS 1489 Part 1)? → **15–35%**

187. 3-day strength of rapid hardening cement roughly equals? → **7-day strength of OPC**

188. Sum of cumulative % retained on standard sieves = 275. Fineness modulus? → **2.75 (275/100; medium sand)**

189. Elongated particle: greatest dimension exceeds what multiple of mean dimension? → **1.8 times**

190. Limit on combined flakiness and elongation index (IS 383:2016)? → **≤ 40%**

191. Maximum aggregate crushing value for concrete other than wearing surfaces? → **45%**

192. SSD mass 1020 g, oven-dry mass 1000 g. Water absorption of aggregate? → **2% ((1020 − 1000)/1000)**

193. Maximum size of coarse aggregate relative to member thickness (IS 456)? → **≤ ¼ of minimum member thickness**

194. Slump recommended by IS 456 for trench fill and in-situ piling? → **100–150 mm**

195. Maximum free fall of concrete to avoid segregation? → **1.5 m**

196. Minimum moist curing for PPC/PSC concrete in normal weather (IS 456)? → **10 days**

197. Partially compacted concrete 22.5 kg, fully compacted 25 kg. Compacting factor? → **0.90 (22.5/25)**

198. Sugar added to concrete acts as? → **Retarder**

199. Latest generation of superplasticiser? → **Polycarboxylate ether (PCE)**

200. Self-compacting concrete was developed by? → **Okamura, Japan (1986)**

201. Modern ferrocement (1940s) was pioneered by? → **P.L. Nervi**

202. Target mean strength for M30 as per IS 10262:2019 (S = 5, X = 6.5)? → **38.25 MPa (30 + 1.65 × 5, higher)**

203. Entrapped air content assumed for 20 mm MSA (IS 10262)? → **1.0%**

204. Water content 180 kg/m³, w/c 0.45. Cement content? → **400 kg/m³ (180/0.45)**

205. Core test acceptance criteria (IS 456 cl 17.4.3)? → **Average ≥ 85% of cube strength; no core < 75%**

206. Cylinder 150 × 300 mm fails at 200 kN in split test. Split tensile strength? → **≈ 2.83 MPa (2P/πDL)**

207. Half-cell potential more negative than −350 mV indicates? → **> 90% probability of rebar corrosion**

208. Who is called the father of prestressed concrete? → **Eugene Freyssinet**

209. Indian code for prestressed concrete? → **IS 1343:2012**

210. Minimum grade of concrete for post-tensioned members (IS 1343:2012)? → **M30**

211. Why is high-tensile steel essential for prestressing? → **Losses (≈ 200–250 N/mm²) would wipe out mild-steel prestress**

212. Anchorage principle of the Freyssinet system? → **Conical wedges (male cone in female cone)**

213. Loss absent in post-tensioning when all tendons are stressed simultaneously? → **Elastic shortening loss**

214. m = 6, concrete stress at tendon level 10 N/mm². Elastic shortening loss (pre-tensioned)? → **60 N/mm² (m f_c)**

215. Shrinkage strain 0.0003, $E_s = 2 \times 10^5$ N/mm². Shrinkage loss? → **60 N/mm² ($\varepsilon_{sh}E_s$)**

216. Prestress force after friction loss at distance x? → **$P_x = P_0 e^{-(\mu\alpha + kx)}$**

217. Kern of a solid circular section? → **Concentric circle of radius D/8**

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218. Transmission length of strands in pre-tensioned members (classic IS 1343)? → **30Φ**

219. Type 1 (full) prestressed member under service load permits? → **No tensile stress**

220. Prestress P = 1500 kN, moment M = 300 kN·m. Shift of pressure line? → **200 mm (M/P)**

14.6 Soil Mechanics & Foundation Engineering (Q 221–270)

221. Black cotton soil is formed from which parent rock? → **Deccan trap basalt**

222. Clay mineral showing the least swelling? → **Kaolinite**

223. Porosity of a soil is 0.4. Void ratio? → **0.667 (n/(1 − n))**

224. Equation of the zero air voids line? → **$\gamma_d = G\gamma_w/(1 + wG)$**

225. Bulk unit weight 19.8 kN/m³, water content 10%. Dry unit weight? → **18.0 kN/m³ (γ/(1 + w))**

226. Relative density range of a dense sand? → **65–85%**

227. LL = 45%, PL = 25%, natural w = 35%. Liquidity index? → **0.5 ((w − PL)/PI)**

228. Activity range of a "normal" clay (Skempton)? → **0.75–1.25**

229. Clay size fraction as per IS 1498? → **Finer than 0.002 mm (2 µm)**

230. Criteria for a well-graded gravel? → **$C_u > 4$ and $1 \le C_c \le 3$**

231. Liquid limit range for intermediate plasticity (IS 1498)? → **35–50%**

232. Rammer mass and drop in modified Proctor test? → **4.9 kg, 450 mm**

233. Clay cores of earth dams are compacted on which side of OMC? → **Slightly wet of optimum**

234. Standard load at 5.0 mm penetration in CBR test? → **2055 kg**

235. Seepage velocity in terms of discharge velocity v? → **$v_s = v/n$**

236. Clean sand with D_{10} = 0.2 mm. Permeability by Hazen (C = 100)? → **0.04 cm/s (100×0.02^2)**

237. Most reliable field method for permeability? → **Pumping-out test**

238. Quick sand condition is most common in which soils? → **Fine sands and silts**

239. Factor of safety usually adopted against piping? → **3 to 4**

240. Time factor T_v for 40% consolidation? → **0.126 ($(\pi/4)U^2$)**

241. Casagrande's log-time fitting method determines? → **t_{50} ($c_v = 0.197d^2/t_{50}$)**

242. NC clay: C_c = 0.3, H = 3 m, e_0 = 1.0, σ′ 100 → 200 kPa. Settlement? → **≈ 135 mm ($C_cH/(1+e_0)$ log 2)**

243. Secondary compression is most significant in? → **Organic soils and peat**

244. Capillary rise is greatest in? → **Clays**

245. Dry sand, φ = 30°, σ_3 = 100 kPa. Major principal stress at failure? → **300 kPa ($\sigma_3 \tan^2(45° + \varphi/2)$)**

246. Triaxial test appropriate for sudden drawdown analysis? → **Consolidated undrained (CU) test**

247. Angle of shearing resistance φ_u of saturated clay in UU test? → **Zero**

248. Point load 100 kN. Boussinesq vertical stress 2 m directly below? → **≈ 11.94 kPa ($0.4775Q/z^2$)**

249. Westergaard influence factor directly below a point load? → **$1/\pi = 0.3183$**

250. Approximate depth of the 0.2q pressure bulb (isobar) below a strip footing? → **About 3B (≈ 1.5B for a square footing)**

251. Coefficient of earth pressure at rest (Jaky)? → **$K_0 = 1 - \sin\varphi'$**

252. Smooth vertical wall 5 m high, dry sand γ = 18 kN/m³, φ = 30°. Active thrust? → **75 kN/m ($\frac{1}{2}K_a\gamma H^2$), at H/3**

253. Earth pressure theory that accounts for wall friction? → **Coulomb's wedge theory**

254. Critical condition for the downstream slope of an earth dam? → **Steady seepage with reservoir full**

255. Bearing capacity factor N_c for φ = 0 per Skempton/IS 6403? → **5.14 (π + 2)**

256. Terzaghi γ-term for a circular footing (B = diameter)? → **$0.3\gamma BN_\gamma$**

257. N_q for φ = 30° as per IS 6403? → **18.40**

258. Punching shear failure occurs in? → **Loose sand and soft clay**

259. Seating load in a plate load test (IS 1888)? → **7 kPa (70 g/cm²)**

260. SPT N-value is the number of blows for? → **Last 300 mm of 450 mm drive**

261. Submerged fine sand, observed N = 25. Dilatancy-corrected N? → **20 (15 + ½(N − 15))**

262. Maximum settlement of isolated foundation on sand (IS 1904)? → **50 mm**

263. Under-reamed piles are mainly used in? → **Expansive (black cotton) soils**

264. Minimum spacing of friction piles (IS 2911)? → **3D**

265. Value of C in ENR formula for drop hammer? → **2.5 cm**

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266. Bearing capacity factor N_c for pile base in clay? → **9**

267. Permissible shift of a well foundation (IRC 78)? → **150 mm**

268. Sampler with D_1 = 50 mm, D_2 = 52 mm. Area ratio? → **8.16% ($(D_2^2 - D_1^2)/D_1^2$)**

269. In RQD, minimum length of core pieces counted? → **100 mm**

270. Soil most susceptible to liquefaction? → **Loose, saturated, uniformly graded fine sand**

14.7 Fluid Mechanics & Hydraulics (Q 271–315)

271. SI unit of dynamic viscosity? → **N·s/m² (Pa·s)**

272. Dimensions of kinematic viscosity? → **L^2T^{-1}**

273. Blood, milk and paints, whose apparent viscosity falls as shear rate rises, are which type of fluid? → **Pseudoplastic (shear-thinning, n < 1)**

274. Surface tension of water in contact with air at 20 °C is about? → **0.073 N/m**

275. Capillary rise of water in a clean glass tube of 3 mm diameter? → **≈ 10 mm (h ≈ 30/d, d in mm)**

276. Excess pressure inside a cylindrical liquid jet of diameter d? → **2σ/d**

277. Cavitation occurs when the local pressure falls below? → **Vapour pressure of the liquid**

278. Gauge pressure at a depth of 5 m below a water surface? → **49.05 kPa (p = ρgh)**

279. Mechanical gauge with an elliptical-section tube bent into a C shape, used for high pressures? → **Bourdon gauge**

280. Depth of centre of pressure of a vertical circular plate of diameter d whose top touches the free surface? → **5d/8**

281. Total water thrust per metre width on a vertical dam face holding 10 m of water? → **490.5 kN (ρgH²/2)**

282. A floating body is in stable equilibrium when? → **Metacentre lies above centre of gravity (GM > 0)**

283. Draft tube is fitted to reaction turbines to? → **Recover exit kinetic energy; allow setting above tailrace**

284. Shape of the free surface of liquid in a forced vortex (rotating vessel)? → **Paraboloid ($z = \omega^2 r^2/2g$)**

285. In steady flow, the local (temporal) acceleration is? → **Zero**

286. Streamlines and equipotential lines intersect each other at? → **Right angles (orthogonal)**

287. Velocity distribution law in a free vortex? → **V × r = constant**

288. In open channel flow, the hydraulic gradient line coincides with? → **The free water surface**

289. Coefficient of discharge of a venturimeter is about? → **0.98 (range 0.95–0.99)**

290. A Hg–water differential manometer on a venturimeter reads 10 cm. Differential head in water? → **1.26 m (h = 12.6x)**

291. Pitot tube in water shows a dynamic head of 0.2 m (C_v = 1). Velocity? → **≈ 1.98 m/s ($V = \sqrt{2gh}$)**

292. Maximum efficiency of a jet striking a single moving flat plate? → **8/27 ≈ 29.6%, at u = V/3**

293. Coefficient of contraction of a sharp-edged orifice is about? → **0.64 (range 0.61–0.69)**

294. Why must a centrifugal pump be primed before starting? → **Air in impeller develops negligible head; suction would fail**

295. Most accurate notch for measuring small discharges? → **Triangular (V) notch**

296. In Francis' weir formula, each end contraction reduces the effective length by? → **0.1 H**

297. A 1% error in measuring head over a rectangular weir gives what error in discharge? → **1.5% ($Q \propto H^{3/2}$)**

298. Discharge over a broad-crested weir is maximum when depth over the crest equals? → **2H/3 (critical depth)**

299. Reynolds number is the ratio of? → **Inertia force to viscous force**

300. Laminar pipe flow at Re = 1600. Darcy friction factor f? → **0.04 (f = 64/Re)**

301. Kinetic energy correction factor α for laminar flow in a circular pipe? → **2.0**

302. Head loss due to sudden enlargement of a pipe? → **$(V_1 - V_2)^2/2g$**

303. For pipes connected in parallel, which quantity is the same in each branch? → **Head loss**

304. Sudden valve closure: V = 2 m/s, c = 1440 m/s. Pressure rise in water? → **2.88 MPa (Δp = ρcV)**

305. Boundary-layer thickness is measured up to the point where u equals? → **0.99 U (free-stream velocity)**

306. Model law used for flow through closed pipes running full? → **Reynolds model law**

307. A 1:16 spillway model follows Froude's law. Discharge scale ratio? → **1024 ($L_r^{5/2}$)**

308. Dimensions of power? → **ML^2T^{-3}**

309. Most economical trapezoidal channel section? → **Half hexagon (sides at 60°, R = y/2)**

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310. Rectangular channel carries q = 2 m³/s/m. Critical depth? → ≈ 0.74 m ($y_c = (q^2/g)^{1/3}$)

311. Hydraulic jump from y_1 = 0.5 m to y_2 = 2.5 m. Energy loss? → 1.6 m ($(y_2-y_1)^3/4y_1y_2$)

312. Flow with Froude number greater than 1 is called? → Supercritical (rapid / shooting) flow

313. Pelton wheel buckets deflect the jet through about? → 165°

314. Which turbine has the highest specific speed? → Kaplan / propeller (axial-flow reaction)

315. A centrifugal pump is started with its delivery valve? → Closed (power is minimum at zero flow)

14.8 Hydrology & Irrigation (Q 316–350)

316. Water budget equation for a catchment? → P − R − G − E − T = ΔS

317. Most important type of precipitation in India? → Orographic

318. Funnel diameter of the Symon's (non-recording) rain gauge? → 127 mm (5 in)

319. Each tip of a tipping-bucket rain gauge records? → 0.25 mm of rain

320. Thiessen areas 60 and 40 km²; rainfalls 50 and 100 mm. Mean areal rainfall? → 70 mm ($\Sigma P_iA_i/\Sigma A_i$)

321. Cetyl alcohol (hexadecanol) film on a reservoir is used to? → Reduce evaporation losses (≈ 20–40%)

322. Class A pan records 10 mm/day evaporation. Lake evaporation? → 7 mm/day (C_p = 0.7)

323. Horton's infiltration equation? → $f_p = f_c + (f_0 - f_c)e^{-kt}$

324. Rational method: C = 0.5, i = 36 mm/h, A = 2 km². Peak discharge? → 10 m³/s (CiA/3.6)

325. Unit hydrograph theory was proposed by? → L. K. Sherman (1932)

326. Unit hydrograph method is generally limited to catchments up to about? → 5000 km²

327. S-curve equilibrium discharge for a 4-h UH of a 360 km² catchment? → ≈ 250 m³/s (2.778A/D)

328. Dicken's constant C_D for north Indian plains? → 6

329. Ryves' formula $Q = C_RA^{2/3}$ is used for which region? → Tamil Nadu (south India)

330. 49-year record; a flood is ranked 2nd. Return period by Weibull? → 25 years (T = (N+1)/m)

331. Sum of Muskingum routing coefficients $C_0 + C_1 + C_2$? → 1

332. Inflow design flood for an intermediate-size dam (IS 11223)? → Standard project flood (SPF)

333. Formation that neither stores nor transmits water (e.g. solid granite)? → Aquifuge

334. Aquifer k = 20 m/day, thickness 30 m. Transmissivity? → 600 m²/day (T = kb)

335. Along a canal system, duty is highest at? → Field / outlet (duty increases downstream)

336. Base period 120 days, duty 1728 ha/cumec. Delta? → 0.6 m (Δ = 8.64B/D)

337. Kor watering depth for wheat? → 13.5 cm

338. Soil moisture tension at permanent wilting point? → ≈ 15 atm (15 bar)

339. Lacey's silt factor in terms of mean particle size d (mm)? → $f = 1.76\sqrt{d}$

340. Kennedy's critical velocity equation (SI)? → $V_0 = 0.55\ m\ D^{0.64}$

341. Cross-drainage work in which the drain passes over the canal and the canal flows freely below? → Super passage

342. Bligh's creep coefficient C for coarse-grained sand? → 12

343. Uplift head 2.48 m on a concrete floor (G = 2.24). Required thickness (no FOS)? → 2.0 m (t = h/(G − 1))

344. Per Khosla, if there is no downstream cut-off (d = 0), the exit gradient becomes? → Infinite – downstream cut-off is essential

345. Gravity dam with reservoir empty: maximum vertical stress occurs at? → Heel

346. Critical condition for the downstream slope of an earth dam? → Steady seepage with reservoir full

347. Energy dissipator when tailwater is deficient at all discharges? → Ski-jump (flip) bucket

348. In a radial (Tainter) gate, the resultant water thrust passes through? → The trunnion pin (small hoisting effort)

349. In a meandering river, erosion takes place on which bank? → Concave (outer) bank

350. Reservoir storage below the minimum drawdown level is called? → Dead storage

14.9 Environmental Engineering (Q 351–400)

351. CPHEEO per-capita supply for towns with piped supply but no sewerage? → 70 lpcd

352. Rural water supply norm under Jal Jeevan Mission? → 55 lpcd

353. Maximum unaccounted-for water permitted by CPHEEO? → 15%

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354. Kuichling's fire demand for a population of 1 lakh? → **31,820 L/min (3182√P, P = 100)**

355. Maximum daily demand as a multiple of average daily demand? → **1.8**

356. Population 1 lakh grows geometrically at 10% per decade. Population after 2 decades? → **1.21 lakh ($P_0(1 + r)^n$)**

357. Acceptable turbidity limit as per IS 10500:2012? → **1 NTU (permissible 5 NTU)**

358. Acceptable limit of iron in drinking water (IS 10500:2012)? → **0.3 mg/L, no relaxation (IS 10500:1991 permitted up to 1.0 mg/L)**

359. Acceptable limit of arsenic in drinking water (IS 10500:2012)? → **0.01 mg/L**

360. Water has Ca^{2+} = 40 mg/L and Mg^{2+} = 24 mg/L. Total hardness? → **200 mg/L as $CaCO_3$ (Ca×2.5 + Mg×4.17)**

361. Temporary (carbonate) hardness is caused by? → **Bicarbonates of calcium and magnesium**

362. Minamata disease is caused by? → **Mercury (methyl mercury)**

363. Settling of discrete particles in plain sedimentation is which type? → **Type I (discrete) settling**

364. Q = 4800 m^3/d, settling tank 20 m × 10 m. Surface overflow rate? → **24 $m^3/m^2/d$ (Q/BL)**

365. Tank volume 1000 m^3, flow 250 m^3/h. Detention time? → **4 h (V/Q)**

366. Optimum coagulant dose is determined by? → **Jar test**

367. Camp–Stein velocity gradient G? → **G = √(P/μV)**

368. Rate of filtration of a rapid sand filter? → **3000–6000 L/h/m^2**

369. Effective size of sand for a slow sand filter? → **0.2–0.35 mm**

370. Mud balls in a rapid sand filter are caused by? → **Inadequate back-washing**

371. Minimum free residual chlorine at consumer's tap (CPHEEO)? → **0.2 mg/L after 30 min contact**

372. Available chlorine in fresh bleaching powder? → **33–35%**

373. Zeolite (base-exchange) softener is regenerated with? → **Common salt (NaCl) brine, 5–10%**

374. Main disadvantage of the dead-end (tree) distribution system? → **Stagnant water at dead ends**

375. Valve that prevents an elevated tank from overflowing? → **Altitude valve**

376. Minimum residual pressure at ferrule for a single-storey building (CPHEEO)? → **7 m**

377. Dry weather flow is taken as what percentage of water supplied (CPHEEO)? → **80%**

378. Minimum diameter of a public sewer (CPHEEO)? → **150 mm**

379. Maximum (non-scouring) velocity generally allowed in sewers by CPHEEO? → **3.0 m/s**

380. BOD test: initial DO 8 mg/L, final DO 2 mg/L, sample 2% by volume. BOD? → **300 mg/L ($(D_1–D_2)/P$)**

381. Ultimate BOD 300 mg/L, k = 0.23 d^{-1} (base e). BOD_5? → **≈ 205 mg/L ($L_0(1 – e^{-kt})$)**

382. Oxidising agent used in the COD test? → **Potassium dichromate ($K_2Cr_2O_7$)**

383. Settled sludge volume 300 mL/L after 30 min; MLSS 2500 mg/L. SVI? → **120 mL/g (V×1000/MLSS)**

384. F/M ratio for a conventional activated sludge plant? → **0.2–0.4 kg BOD/kg MLVSS/d**

385. India's first UASB sewage treatment plant was built at? → **Kanpur (Jajmau), 1989**

386. Sludge thickened from 98% to 95% moisture. New volume as fraction of original? → **0.4 (V_2/V_1 = 2/5)**

387. Methane content of digester gas? → **65–70%**

388. Minimum DO for CPCB Class A water (drinking after disinfection)? → **6 mg/L**

389. Rain is termed acid rain when its pH is below? → **5.6**

390. Coning plume occurs under which atmospheric condition? → **Neutral / slightly stable**

391. NAAQS 2009 annual limit of SO_2 for industrial/residential areas? → **50 μg/m^3**

392. Overall Indian AQI is taken as? → **Maximum of the pollutant sub-indices**

393. Solid Waste Management Rules, 2026 came into force on? → **1 April 2026, replacing SWM Rules 2016**

394. Bulk waste generator under SWM Rules 2026? → **Built-up > 20,000 m^2, water > 40,000 L/day, or waste > 100 kg/day**

395. Minimum composting temperature needed to kill pathogens? → **≈ 55 °C (thermophilic)**

396. Bag colour for human anatomical waste (BMW Rules 2016)? → **Yellow – incineration / plasma pyrolysis / deep burial**

397. Large C&D waste generator under C&D Rules 2016? → **≥ 20 t/day or 300 t per project per month**

398. Two sources of 80 dB and 70 dB operate together. Resultant level? → **≈ 80.4 dB ($10 \log \Sigma 10^{L/10}$)**

399. Point source gives 90 dB at 10 m. Level at 40 m (free field)? → **≈ 78 dB (–6 dB per doubling)**

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400. Day-time noise limit in a silence zone? → **50 dB(A) (night 40 dB(A))**

14.10 Transportation Engineering (Q 401–445)

401. Road density target of the Bombay Plan (1961–81)? → **32 km per 100 km²**

402. In which year was the Central Road Fund set up? → **1929 (from the petrol cess)**

403. Central Road Research Institute (CRRI), New Delhi, was set up in? → **1952**

404. Under the 2010 NH numbering, east–west highways carry which numbers? → **Odd numbers (north–south highways are even)**

405. PMGSY was launched on? → **25 December 2000**

406. PCU value of a truck or bus on rural roads (IRC 64)? → **3.0**

407. Camber for a cement concrete road in heavy rainfall (IRC)? → **2.0% (1 in 50)**

408. Width of a single-lane carriageway (IRC)? → **3.75 m**

409. Maximum width of a vehicle as per IRC 3? → **2.5 m**

410. Heights of driver's eye and object adopted by IRC for SSD? → **1.2 m and 0.15 m**

411. SSD for V = 72 km/h, t = 2.5 s, f = 0.36? → **≈ 106.7 m (50 + 5184/(254 × 0.36))**

412. OSD on a divided highway (one-way traffic) consists of? → **$d_1 + d_2$ only (no d_3)**

413. Maximum superelevation on hill roads not bound by snow (IRC)? → **10%**

414. Superelevation to be computed for V = 80 km/h, R = 500 m? → **0.057 ($V^2/225R$ = 6400/112500)**

415. Rate of change of superelevation in plain and rolling terrain? → **1 in 150**

416. Ruling minimum radius for V = 100 km/h, e + f = 0.22? → **≈ 358 m ($V^2/127(e + f)$)**

417. Two-lane road, wheel base 6 m, R = 100 m. Mechanical widening? → **0.36 m ($nl^2/2R$ = 2 × 36/200)**

418. Limiting gradient in plain and rolling terrain (IRC)? → **5% (1 in 20)**

419. Grade compensation on a curve of radius 60 m? → **1.25% (75/R governs over (30 + R)/R)**

420. Valley curves are designed on the basis of? → **Headlight sight distance and comfort**

421. Standard load at 5.0 mm penetration in the CBR test? → **2055 kg**

422. Test load at 2.5 mm penetration is 68.5 kg. CBR value? → **5% (68.5/1370 × 100)**

423. Diameter of the plate in the plate bearing test for k value? → **75 cm**

424. Maximum Los Angeles abrasion value for bituminous concrete (MoRTH)? → **30%**

425. Height of fall of the hammer in the aggregate impact test? → **380 mm**

426. An aggregate is called flaky when its least dimension is less than? → **0.6 × mean dimension**

427. Standard conditions of the bitumen penetration test? → **100 g needle, 5 s, 25 °C**

428. Cutback bitumen commonly used for prime coat? → **Medium curing (MC) cutback**

429. Marshall compaction blows per face for heavy traffic? → **75**

430. Minimum Marshall stability at 60 °C for DBM/BC (MoRTH)? → **9.0 kN**

431. G_t = 2.50 and G_m = 2.40 for a bituminous mix. Air voids? → **4% ((2.50 − 2.40)/2.50 × 100)**

432. Minimum grade of concrete for rigid pavements as per IRC 58:2015? → **M40 (flexural strength ≥ 4.5 MPa)**

433. Damage factor of a 120 kN single axle relative to the 80 kN standard axle? → **≈ 5.06 ($(120/80)^4$)**

434. Lane distribution factor for a two-lane single carriageway (IRC 37)? → **0.5**

435. Dowel bars in rigid pavements are provided at? → **Transverse joints (plain round bars)**

436. Standard temperature for Benkelman beam deflection correction (IRC 81)? → **35 °C**

437. Bleeding of a bituminous surface is mainly caused by? → **Excess bitumen / low air voids in hot weather**

438. Which percentile speed is used for geometric design? → **98th percentile speed**

439. Greenshields model: v_f = 80 km/h, k_j = 120 veh/km. Maximum flow? → **2400 veh/h ($v_f k_j/4$)**

440. Shape of the STOP sign? → **Octagonal, red with white letters**

441. Total conflict points at a 4-legged uncontrolled intersection? → **32 (16 crossing, 8 merging, 8 diverging)**

442. Width of standard gauge? → **1435 mm**

443. Equilibrium cant on BG (G = 1750 mm) for V = 80 km/h, R = 1000 m? → **≈ 88 mm ($GV^2/127R$)**

444. Maximum cant on BG track (normal routes, IRPWM)? → **165 mm**

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445. Permissible crosswind component for reference field length ≥ 1500 m (ICAO)? → **37 km/h (20 knots)**

14.11 Surveying, GIS & GPS (Q 446–480)

446. Spherical excess of a triangle is about 1″ for an area of? → **≈ 195.5 km²**

447. Approximate orbital altitude of GPS satellites? → **≈ 20,200 km (12-hour orbit)**

448. Low value of DOP in GNSS indicates? → **Good (widely spread) satellite geometry, better accuracy**

449. Advantage of a graphical scale on a map? → **Remains correct even if the map shrinks**

450. Direct vernier: 10 vernier divisions = 9 main divisions of 1 mm. Least count? → **0.1 mm (s/n = 1/10)**

451. Usual contour interval on a 1:25,000 SoI toposheet? → **10 m**

452. Typical real-time accuracy of RTK GNSS? → **1–2 cm (carrier-phase)**

453. Contours merging into a single line indicate? → **Vertical cliff**

454. Angle limits of a well-conditioned triangle in chain surveying? → **Between 30° and 120°**

455. Length of Gunter's chain? → **66 ft, 100 links**

456. Invar tape is an alloy of steel with? → **36% nickel**

457. A 30 m chain is 5 cm too short. Measured length 600 m. True length? → **599.0 m (600 × 29.95/30)**

458. Tape corrections that are always negative? → **Sag and slope (MSL correction is negative only for lines above MSL)**

459. WCB of 135° expressed as reduced bearing? → **S 45° E**

460. Sum of interior angles of a closed hexagonal traverse? → **720° ((2n − 4) × 90°)**

461. GAGAN is India's? → **SBAS by ISRO and AAI for civil aviation**

462. Levelling method giving a check on intermediate RLs? → **Rise and fall method**

463. Refraction correction in levelling (d in km)? → **0.0112 d² m, additive**

464. Distance to visible horizon from a height of 9 m? → **≈ 11.6 km (3.855√h)**

465. Correct order for eliminating parallax? → **Focus eyepiece first, then objective**

466. Theodolite adjustment for horizontal axis ⊥ vertical axis? → **Spire test**

467. Theodolite error NOT eliminated by face left and face right? → **Vertical axis not truly vertical**

468. Transit rule of traverse balancing is used when? → **Angular measurements more precise than linear**

469. ΣL = 0.3 m, ΣD = −0.4 m, perimeter 1500 m. Relative precision? → **1 in 3000 (e = 0.5 m)**

470. Usual multiplying constant of a tacheometer? → **100**

471. Least accurate triangulation figure, used for narrow strips? → **Chain of single triangles**

472. Plane table method for locating inaccessible points? → **Intersection (graphical triangulation)**

473. Three-point problem becomes indeterminate when the station lies on? → **The danger circle**

474. Vertical photo: f = 152 mm, H = 3500 m, h = 460 m. Scale? → **1:20,000 (f/(H − h))**

475. Radius of a 4° curve (20 m arc)? → **≈ 286.5 m (1145.9/D)**

476. Chainage of the point of tangency (T_2) equals? → **Chainage of T_1 + curve length**

477. Vector GIS surface model of irregular Delaunay triangles? → **TIN (Triangulated Irregular Network)**

478. Rankine's deflection angle for chord c on radius R? → **1718.9 c/R minutes**

479. Altitude of a geostationary satellite? → **≈ 35,786 km**

480. Formula for NDVI? → **(NIR − Red)/(NIR + Red)**

14.12 Project Management, Estimating & Contracts (Q 481–500)

481. Father of scientific management? → **F.W. Taylor**

482. Organisation with dual reporting to project and functional managers? → **Matrix organisation**

483. A project is acceptable on BCR when? → **BCR > 1**

484. CPM was developed in 1957 by? → **Du Pont & Remington Rand (Kelley and Walker)**

485. Dummy ensuring no two activities share the same i–j? → **Uniqueness (identity) dummy**

486. In the forward pass, at a merge event, take? → **Maximum of ($E_i + t_{ij}$)**

487. Formula for free float of activity i–j? → **$E_j - E_i - t_{ij}$**

488. PERT: t_o = 3, t_m = 6, t_p = 15 days. t_e and σ? → **7 days; σ = 2 ((3 + 24 + 15)/6; 12/6)**

489. T_E = 50 d, σ = 5 d. Probability of completion in 45 d? → **≈ 15.9% (Z = −1)**

490. Normal 12 d at ₹6,000; crash 8 d at ₹9,000. Cost slope? → **₹750/day (3000/4)**

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491. CPI less than 1 indicates? → **Cost overrun (over budget)**

492. As per the CPWD Works Manual, a revised estimate is needed when the sanctioned estimate is exceeded by? → **More than 10% (older textbooks quote 5%)**

493. Approximate estimate method for godowns with repeated bays? → **Bay method**

494. Weight of 10 m of 20 mm diameter bar? → **≈ 24.7 kg ($D^2/162 \times 10$)**

495. Unit of measurement of formwork (IS 1200)? → **m² of area in contact with concrete**

496. Plastering deduction for an opening of 2 m² (IS 1200)? → **Deduct one face only; no jambs/sills added**

497. Book value of a property equals? → **Original cost − total depreciation to date**

498. Contract where the contractor quotes a % above/below estimated cost? → **Percentage rate contract**

499. Ceiling of liquidated damages in CPWD contracts? → **10% of tendered value (1.5% per month)**

500. Equipment for vertical digging in cofferdams and wells? → **Clamshell**

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