Foundation Engineering

Short notes for B.Tech Civil · GATE CE

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I. Introduction and Soil Exploration

- **Foundation** = lowest part of a structure that transfers load safely to the soil.
- Two basic checks: shear failure (bearing capacity) and settlement within limits.
- **Shallow foundation**: depth Df ≤ width B (Terzaghi). Examples: isolated, combined, strip, raft.
- **Deep foundation**: Df > B. Examples: piles, piers, wells (caissons).

➤ Site investigation

- Stages: reconnaissance, preliminary exploration, detailed exploration.
- Methods: test pits (shallow), auger boring, wash boring, rotary drilling, percussion drilling.
- **Geophysical**: electrical resistivity, seismic refraction (fast, cover large area, need checking by borings).

➤ Sampling

FORMULA Area ratio $Ar = (Do^2 - Di^2) / Di^2 \times 100$. Keep Ar ≤ 10% for good undisturbed samples.

- Inside clearance (Ci) reduces friction inside the tube; outside clearance helps withdrawal.
- **Recovery ratio** = recovered length / penetration length.
- Samplers: open drive (Shelby tube), piston sampler (soft clay), split spoon (SPT, disturbed).

➤ Standard Penetration Test (SPT)

- 63.5 kg hammer, 750 mm free fall, split spoon driven 450 mm. **N = blows for the last 300 mm**.

- Corrections: overburden correction (for sand), dilatancy correction for fine sand / silt below water table:

FORMULA Dilatancy correction (when $N > 15$): $N' = 15 + 0.5\,(N - 15)$.

- N is used for ϕ of sand, bearing capacity and settlement of footings on sand.
- Other in-situ tests: static cone penetration test (SCPT, cone resistance q_c), dynamic cone, vane shear, pressuremeter, plate load test.

2. Bearing Capacity of Shallow Foundations

Term	Meaning
Ultimate bearing capacity q_u	Gross pressure at shear failure
Net ultimate q_{nu}	$q_u - \gamma D_f$
Net safe q_{ns}	q_{nu} / FS (FS usually 2.5 to 3)
Safe bearing capacity q_s	$q_{ns} + \gamma D_f$
Allowable bearing pressure	Lower of q_{ns} and pressure for permissible settlement

➤ Modes of shear failure

Mode	Soil	Feature
General shear	Dense sand, stiff clay	Clear failure surface, heave on both sides, sudden
Local shear	Medium dense soil	Failure surface not fully developed
Punching shear	Loose sand, soft clay	Large settlement, no heave

➤ Terzaghi's equations

FORMULA Strip: $q_u = c\,N_c + \gamma D_f N_q + 0.5\,\gamma B N_\gamma$.

FORMULA Square: $q_u = 1.3\,c\,N_c + \gamma D_f N_q + 0.4\,\gamma B N_\gamma$. Circular: $q_u = 1.3\,c\,N_c + \gamma D_f N_q + 0.3\,\gamma B N_\gamma$.

- N_c, N_q, N_γ depend on ϕ only. For $\phi = 0$ (Terzaghi): $N_c = 5.7$, $N_q = 1$, $N_\gamma = 0$.
- **Local shear**: use $c' = (2/3)\,c$ and $\tan\phi' = (2/3)\tan\phi$.
- Skempton (clay, $\phi = 0$): $N_c = 5$ for strip and 6 for square / circle at the surface; increases with depth.

- Meyerhof, Hansen and IS 6403 add shape, depth and inclination factors.

➤ Effect of water table

- Water table at the base or above reduces the surcharge term (use γ'); within depth B below the base reduces the $N\gamma$ term.
- Reduction factor for the $N\gamma$ term: $Rw = 0.5\ (1 + 2w / B)$, $2w$ = depth of WT below the base (0 to B).

EXAMPLE Strip footing B = 2 m, Df = 1 m, c = 0, γ = 18 kN/m³, ϕ = 30° (take Nq = 22.5, $N\gamma$ = 19.7). qu = 18 x 1 x 22.5 + 0.5 x 18 x 2 x 19.7 = 405 + 354.6 = 759.6 kPa. qnu = 759.6 - 18 = 741.6 kPa. qns (FS 3) = 247.2 kPa. qs = 247.2 + 18 = 265.2 kPa.

3. Settlement and Plate Load Test

- Total settlement = immediate (elastic) + primary consolidation + secondary compression.
- Immediate settlement $Si = q\ B\ (1 - \mu^2)\ If / Es$. Main settlement in sand.
- Consolidation settlement is main in clay (see Soil Mechanics).
- **Differential settlement** causes cracks; angular distortion = differential settlement / distance between columns.

➤ Plate load test

- Plate 300 to 750 mm square, loaded in steps; settlement recorded until it becomes very small.
- Gives load–settlement curve, ultimate bearing capacity and modulus of subgrade reaction.

FORMULA Sand: $Sf = Sp\ [B\ (Bp + 0.3) / (Bp\ (B + 0.3))]^2$. Clay: $Sf = Sp \times B / Bp$. Bearing capacity in clay is the same as plate; in sand $qf = qp \times B/Bp$.

EXAMPLE Plate 0.3 m settles 10 mm in sand under the design pressure. Footing B = 2 m. $Sf = 10 \times [2 \times 0.6 / (0.3 \times 2.3)]^2 = 10 \times (1.739)^2 = 30.2$ mm.

- Limitations: tests only about 2 times the plate width in depth; short-term test, not good for clay consolidation.

4. Types of Shallow Foundations

Type	When used
Isolated footing	Single column, good soil
Combined footing	Two columns close together or one near the property line
Strip (wall) footing	Load-bearing walls
Strap (cantilever) footing	Exterior column at property line, joined by a strap beam to an interior footing
Raft (mat)	Weak soil, footings cover more than about half the plan area, reduces differential settlement

- Combined footing: make the centroid of the footing coincide with the resultant of column loads, so pressure is uniform.
  - Rectangular if the outer column carries less load; trapezoidal if the outer column carries more load.
- **Floating (compensated) raft**: weight of excavated soil ≈ building load, so net pressure is near zero.
- Eccentric load: $q = (P/A)(1 \pm 6e/B)$. Keep $e \le B/6$ so no tension under the footing.

5. Pile Foundations

➤ Classification

- By function: end bearing, friction, compaction, tension (uplift), anchor, batter (lateral load), fender.
- By material: timber, concrete (precast / cast-in-situ, bored / driven), steel (H-pile, pipe), composite.
- **Under-reamed piles**: bored piles with bulbs; used in expansive (black cotton) soils.

➤ Static formula

FORMULA $Qu = Qb + Qs = qb\ Ab + \Sigma\ fs\ As$. In clay: $Qb = 9\ cu\ Ab$, $Qs = \alpha\ \bar{c}u\ As$ (α = adhesion factor).

- In sand: $Qb = \sigma'v\ Nq\ Ab$ ($\sigma'v$ stops increasing below a critical depth), $Qs = K\ \sigma'v\ \tan\delta\ As$.

EXAMPLE Bored pile $d = 0.4$ m, $L = 12$ m in clay, $c_u = 50$ kPa, $\alpha = 0.7$. $A_b = 0.1257$ m², $A_s = \pi \times 0.4 \times 12 = 15.08$ m². $Q_b = 9 \times 50 \times 0.1257 = 56.6$ kN. $Q_s = 0.7 \times 50 \times 15.08 = 527.8$ kN. $Q_u = 584.4$ kN. Q_a (FS 2.5) = 233.7 kN.

Dynamic formulae

FORMULA Engineering News formula: $Q_a = W H / [6 (S + C)]$, W in kN, H and S in cm, $C = 2.5$ cm (drop hammer) or 0.25 cm (steam hammer). FS = 6 is built in.

- Hiley's formula includes hammer efficiency and energy losses. Dynamic formulae are poor for clays.
- **Pile load test**: vertical initial (on test pile) and routine tests; cyclic test separates skin friction and end bearing.

Pile groups

- Minimum spacing about 2.5d to 3d. Group capacity in sand often more than the sum (compaction); in clay less.

FORMULA Converse–Labarre efficiency: $\eta = 1 - (\theta/90)\,[(n - 1)m + (m - 1)n] / (m\,n)$, $\theta = \tan^{-1}(d/s)$ in degrees.

FORMULA Block failure in clay: $Q_g = c_u N_c A_b + c_u \times \text{perimeter} \times L$. Group capacity = lesser of (block value) and ($\eta \times n \times Q_{single}$).

EXAMPLE 3 × 3 group, $d = 0.4$ m, $s = 1.2$ m. $\theta = \tan^{-1}(0.4/1.2) = 18.43°$. $\eta = 1 - (18.43/90) \times [2 \times 3 + 2 \times 3]/9 = 1 - 0.2048 \times 1.333 = 0.727$ (72.7%).

- **Negative skin friction**: soft fill or clay settling around the pile drags it down. It adds load: Q_{nf} = perimeter × length × α c_u (clay).
- Settlement of a group is larger than that of a single pile (bigger pressure bulb).

6. Well Foundations and Caissons

- Used for bridge piers and abutments in rivers with deep scour.
- Parts: cutting edge, curb, steining, bottom plug, sand filling, top plug, well cap.
- Shapes: circular (most common), double-D, dumb-bell, rectangular.

- Sinking problems: **tilt and shift** (corrected by eccentric loading, dredging on the high side, pulling, jetting).
- **Grip length** = depth below maximum scour level. Scour depth by Lacey: $d = 0.473 (Q/f)^{(1/3)}$.
- Caisson types: open (well), pneumatic (compressed air, risk of caisson disease), box (floating).

7. Retaining Walls, Sheet Piles and Ground Improvement

➤ Stability checks of retaining walls

1. **Overturning**: resisting moment / overturning moment (commonly FS ≥ 2).
2. **Sliding**: $\mu \Sigma V / \Sigma H$ (commonly FS ≥ 1.5).
3. **Bearing pressure**: max base pressure ≤ safe bearing capacity; no tension ($e \leq B/6$).
4. Overall (deep-seated) stability.

- Types: gravity, cantilever, counterfort, buttress, reinforced earth.
- **Sheet pile walls**: cantilever (small heights) and anchored (free earth support, fixed earth support).
- **Braced cuts**: apparent pressure diagrams of Peck are used for strut loads.
- **Cofferdams**: temporary enclosures to work in dry (earth, cellular, single / double wall).

➤ Ground improvement

Method	Soil
Vibroflotation	Loose sand
Dynamic compaction	Loose granular fill
Preloading with sand drains / PVDs	Soft clay (faster consolidation)
Stone columns	Soft clay, loose silty sand
Grouting	Fissured rock, gravel
Lime / cement stabilisation	Expansive clay

REMEMBER Vertical drains shorten the drainage path, so consolidation time drops sharply (time $\propto d^2$).

➤ Expansive soils

- Black cotton soil: montmorillonite, high swelling and shrinkage. Use under-reamed piles, CNS (cohesive non-swelling) layer, moisture control.

8. Most Asked Questions (practice)

1. Explain SPT, its procedure and corrections.
2. Define area ratio and inside clearance. Why are they limited?
3. Explain the three modes of shear failure with sketches.
4. Derive / state Terzaghi's bearing capacity equation; find q_u for a square footing.
5. Explain the effect of water table on bearing capacity.
6. Describe the plate load test and its limitations.
7. Design proportions of a combined (rectangular / trapezoidal) footing.
8. Find pile capacity by static formula in clay and sand.
9. Find group efficiency and group capacity in clay; explain negative skin friction.
10. Explain components of a well foundation and remedies for tilt and shift.

TIP GATE CE often asks Terzaghi bearing capacity with water table, pile capacity in clay, group efficiency and plate load settlement. Learn the net vs gross pressure difference clearly.