

Civil Engineering FE CBT Exam

Knowledge: Geotechnical Engineering with 20 Example Problems

Contents

1 Index Properties & Soil Classification	2
1.1 Sieve Analysis and Grain-Size Curves	2
1.2 Atterberg Limits	2
1.3 Unified Soil Classification System (USCS)	2
1.4 AASHTO Soil Classification System	3
2 Phase Relations.....	3
2.1 Fundamental Phase Definitions.....	3
2.2 Critical Phase Identity	3
2.3 Unit Weight Formulas	4
2.4 Relative Density (Dr).....	4
3 Laboratory and Field Tests	4
3.1 Standard and Modified Proctor Compaction Tests	5
3.2 Zero-Air-Voids (ZAV) Line	5
3.3 Field Quality Control and Relative Compaction (RC).....	5
4 Effective Stress & Pore Water Pressure	5
4.1 Total Stress, Pore Pressure, and Effective Stress	5
4.2 Surface Surcharge Effects.....	6
4.3 Seepage Exit Gradient and Liquefaction	6
5 Stability of Retaining Structures	6
5.1 Rankine Lateral Earth Pressure Coefficients.....	6
5.2 Horizontal Pressure Distributions and Resultant Forces	6
6 Shear Strength of Soil.....	6
6.1 Mohr-Coulomb Failure Criterion	7
6.2 Triaxial Compression Testing.....	7
7 Bearing Capacity of Shallow Foundations.....	7
7.1 Terzaghi Ultimate Bearing Capacity Equation.....	8
7.2 Allowable Bearing Capacity and Safety Factor.....	8
7.3 Eccentric Footing Loading and Base Pressures.....	8
8 Foundation Selection and Types	8
9 Consolidation & Differential Settlement.....	9
9.1 Consolidation Parameters and Indices.....	9
9.2 Primary Consolidation Settlement (H) Δ	9
10 Slope Stability Analysis	9
10.1 Planar Slip Surface Model.....	9
11 Soil Stabilization Methods.....	10
12 Example Problems and Solutions (20 Problems)	11

1 Index Properties & Soil Classification

Soil index properties quantify soil physical state and grain-size characteristics, providing the basis for engineering soil classification under the **Unified Soil Classification System (USCS)** and **AASHTO Soil Classification System**.

1.1 Sieve Analysis and Grain-Size Curves

Particle-size distribution parameters are determined from sieve analysis and hydrometer tests:

- D_{10} (Effective Size): Particle diameter corresponding to 10% finer by weight.
- D_{30} : Particle diameter corresponding to 30% finer by weight.
- D_{60} : Particle diameter corresponding to 60% finer by weight.

Gradation Coefficients (FE Handbook 10.6)

$$\text{Coefficient of Uniformity: } C_u = \frac{D_{60}}{D_{10}}$$

$$\text{Coefficient of Curvature (Concavity): } C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$$

Gradation rules below apply to clean coarse soils (< 5% fines); fines content governs symbols.

- **Well-Graded Sand (SW):** $C_u \geq 6$ and $1 \leq C_c \leq 3$.
- **Well-Graded Gravel (GW):** $C_u \geq 4$ and $1 \leq C_c \leq 3$.
- **Poorly Graded (SP / GP):** Fails either the C_u or C_c criteria.
- **Uniformly Graded:** Particle size distribution curve is nearly vertical (narrow range of sizes).
- **Gap-Graded:** Horizontal step in distribution curve (missing intermediate grain sizes).

1.2 Atterberg Limits

Atterberg limits define the boundary moisture contents separating soil physical states for fine-grained soils:

- **Liquid Limit (LL):** Water content at transition between liquid and plastic state (determined using Casagrande Cup or Fall Cone device).
- **Plastic Limit (PL):** Water content at which a 3.2 mm (1/8 inch) soil thread crumbles when rolled.
- **Plasticity Index (PI):** Range of water content over which soil exhibits plastic behavior.

Plasticity Index Formula

$$PI = LL - PL$$

1.3 Unified Soil Classification System (USCS)

USCS categorizes soil into Coarse-Grained (< 50% passing No. 200 sieve) and Fine-Grained ($\geq$ 50% passing No. 200 sieve, where No. 200 sieve mesh opening = 0.075 mm).

A-Line Equation on Plasticity Chart:

$$\text{A-Line: } PI = 0.73(LL - 20)$$

$$\text{U-Line (Upper Limit): } PI = 0.9(LL - 8)$$

Classification Rules:

- Points above the A-Line represent Clay (*C*).
- Points below the A-Line generally indicate Silt (*M*); Organic (*O*) classification requires additional organicity criteria.
- Soils with $LL \geq 50$ are high plasticity (*H*); $LL < 50$ are low plasticity (*L*).
- Dual symbols (e.g., $CL - ML$) apply if $4 \leq PI \leq 7$ and plots in the hatched zone.
- Coarse soils: 5–12% fines use dual symbols; $> 12\%$ use fines plasticity classification.

1.4 AASHTO Soil Classification System

Used primarily for highway subgrade rating. Classifies soils into Groups A-1 through A-7 based on sieve passing percentages (No. 10, No. 40, No. 200), LL , and PI .

AASHTO Group Index (GI) Formula

$$GI = (F_{200} - 35)[0.2 + 0.005(LL - 40)] + 0.01(F_{200} - 15)(PI - 10)$$

Use standard AASHTO limits for F_{200} , LL , and PI ; set negative terms to zero; round GI to nearest nonnegative integer.

2 Phase Relations

Soil is a three-phase system composed of Solid mineral grains, Liquid (Water), and Gas (Air).

2.1 Fundamental Phase Definitions

Let total volume $V = V_s + V_v = V_s + V_w + V_a$, and total mass/weight $W = W_s + W_w$ (air weight $W_a \approx 0$).

Key Phase Formulas (FE Handbook 10.6)

$$\text{Void Ratio: } e = \frac{V_v}{V_s} \quad \text{Porosity: } n = \frac{V_v}{V} = \frac{e}{1 + e}$$

$$\text{Water Content (\%): } w = \frac{W_w}{W_s} \times 100 \quad \text{Degree of Saturation (\%): } S = \frac{V_w}{V_v} \times 100$$

$$\text{Specific Gravity of Solids: } G_s = \frac{W_s/V_s}{\gamma_w} = \frac{\rho_s}{\rho_w}$$

2.2 Critical Phase Identity

The fundamental soil phase relationship linking S , e , w , and G_s :

Golden Phase Identity

$$S \cdot e = w \cdot G_s$$

Use S and w as fractions in $Se = wG_s$; saturated soil has $S = 1$.

2.3 Unit Weight Formulas

Unit weights dictate vertical stress calculations in geotechnical analysis:

- **Unit Weight of Water (γ_w):** 62.4 pcf (lb/ft³) or 9.81 kN/m³.
- **Total / Moist Unit Weight (γ):** $\gamma = \frac{W}{V} = \frac{G_s + Se}{1+e} \gamma_w = \gamma_d(1+w)$.
- **Dry Unit Weight (γ_d):** $\gamma_d = \frac{W_s}{V} = \frac{G_s \gamma_w}{1+e} = \frac{\gamma}{1+w}$.
- **Saturated Unit Weight (γ_{sat}):** $\gamma_{sat} = \frac{G_s + e}{1+e} \gamma_w$.
- **Submerged / Effective Unit Weight (γ'):** $\gamma' = \gamma_{sat} - \gamma_w = \frac{G_s - 1}{1+e} \gamma_w$.

2.4 Relative Density (Dr)

Characterizes state of packing for coarse-grained granular soils:

Relative Density (NCEES Handbook p. 260)

$$D_r = \left[\frac{e_{\max} - e}{e_{\max} - e_{\min}} \right] \times 100\% = \left[\frac{\gamma_{d,\text{field}} - \gamma_{d,\min}}{\gamma_{d,\max} - \gamma_{d,\min}} \right] \left[\frac{\gamma_{d,\max}}{\gamma_{d,\text{field}}} \right] \times 100\%$$

3 Laboratory and Field Tests

Laboratory and field compaction tests establish maximum dry density and optimum moisture content for structural earth fills.

3.1 Standard and Modified Proctor Compaction Tests

Compaction increases dry unit weight by expelling air voids at a given moisture content:

- **Standard Proctor (ASTM D698):** 5.5-lb hammer, 12-in. drop, three layers; 25 blows/layer with a 4-in. mold or 56 with a 6-in. mold.
- **Modified Proctor (ASTM D1557):** 10-lb hammer, 18-in. drop, five layers; 25 blows/layer with a 4-in. mold or 56 with a 6-in. mold.
- Higher compaction energy increases $\gamma_{d,\max}$ and decreases Optimum Moisture Content (OMC).

3.2 Zero-Air-Voids (ZAV) Line

Represents theoretical maximum dry unit weight at 100% degree of saturation ($S = 1.0$):

$$\gamma_{\text{zav}} = \frac{G_s \gamma_w}{1 + w \cdot G_s}$$

3.3 Field Quality Control and Relative Compaction (RC)

Field density is verified using Sand-Cone Method (ASTM D1556) or Nuclear Density Gauge (ASTM D6938).

Relative Compaction

$$RC = \left(\frac{\gamma_{d,\text{field}}}{\gamma_{d,\max,\text{lab}}} \right) \times 100\%$$

Typically, specs require $RC \geq 95\%$ of Standard or Modified Proctor maximum dry density.

4 Effective Stress & Pore Water Pressure

Karl Terzaghi's Principle of Effective Stress governs soil shear strength, volume change, and lateral pressures.

4.1 Total Stress, Pore Pressure, and Effective Stress

At any depth z :

Terzaghi Effective Stress Principle

$$\sigma' = \sigma - u$$

where $\sigma = \sum \gamma_i h_i$ (Total Vertical Stress), $u = h_w \gamma_w$ (Hydrostatic Pore Water Pressure), and σ' is Effective Vertical Stress transmitted across particle contact points.

4.2 Surface Surcharge Effects

A uniform surface surcharge S (in psf or kPa) increases total stress and effective stress equally across all depths under drained conditions:

$$\sigma = S + \sum \gamma_i h_i \implies \sigma' = S + \sum \gamma_i h_i - u$$

4.3 Seepage Exit Gradient and Boiling

Upward seepage through soil reduces effective stress. When $u = \sigma$, effective stress becomes zero (quick condition / boiling / piping failure).

Critical Hydraulic Gradient and Boiling Safety Factor

$$i_c = \frac{\gamma'}{\gamma_w} = \frac{G_s - 1}{1 + e}, \quad FS_s = \frac{i_c}{i_e}$$

$i_e = \Delta h/L$. This is an upward-seepage check, not an earthquake liquefaction check.

5 Stability of Retaining Structures

Retaining structures resist horizontal soil pressures exerted by retained soil masses.

5.1 Rankine Lateral Earth Pressure Coefficients

For level backfill and smooth vertical walls ($c = 0$):

Rankine Earth Pressure Coefficients (FE Handbook 10.6)

$$\text{Active Pressure Coefficient: } K_a = \tan^2 \left(45^\circ - \frac{\phi}{2} \right) = \frac{1 - \sin \phi}{1 + \sin \phi}$$

$$\text{Passive Pressure Coefficient: } K_p = \tan^2 \left(45^\circ + \frac{\phi}{2} \right) = \frac{1 + \sin \phi}{1 - \sin \phi} = \frac{1}{K_a}$$

$$\text{At-Rest Coefficient (Normally Consolidated): } K_0 \approx 1 - \sin \phi$$

5.2 Horizontal Pressure Distributions and Resultant Forces

Active lateral effective pressure at depth z :

$$\sigma'_a = \sigma'_v K_a - 2c\sqrt{K_a}$$

For a dry/drained cohesionless soil wall of height H :

$$P_A = \frac{1}{2} \gamma H^2 K_a \quad (\text{acts at } H/3 \text{ above base})$$

If water table is present at depth H_1 , total horizontal force combines effective soil pressure and full hydrostatic water pressure.

6 Shear Strength of Soil

Soil shear resistance is modeled by the Mohr-Coulomb failure envelope.

6.1 Mohr-Coulomb Failure Criterion

Mohr-Coulomb Criterion (NCEES Handbook p. 263)

$$\tau_F = c + \sigma_N \tan \phi$$

where c is cohesion, σ_N is normal stress on failure plane, and ϕ is internal friction angle. In effective stress terms: $\tau_F = c' + \sigma'_N \tan \phi'$.

6.2 Triaxial Compression Testing

Standard test types: Unconsolidated-Undrained (UU), Consolidated-Undrained (CU), Consolidated-Drained (CD).

Principal Stress Relationship at Failure

$$\sigma_1 = \sigma_3 \tan^2 \left(45^\circ + \frac{\phi}{2} \right) + 2c \tan \left(45^\circ + \frac{\phi}{2} \right) = \sigma_3 K_p + 2c\sqrt{K_p}$$

For cohesionless soil ($c = 0$): $\sin \phi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3}$.

7 Bearing Capacity of Shallow Foundations

Shallow footings transmit structural column loads to supporting soil strata without shear failure or excessive settlement.

7.1 Terzaghi Ultimate Bearing Capacity Equation

For a continuous strip footing of width B at depth D_f :

Terzaghi Bearing Capacity (FE Handbook 10.6)

$$q_{ult} = cN_c + qN_q + \frac{1}{2}\gamma_b B N_\gamma$$

q : effective overburden at the base; γ_b : appropriate bearing-zone unit weight. Treat groundwater effects separately in these terms.

Footing Shape Adjustments:

- **Square footing** ($B \times B$): $q_{ult} = 1.3cN_c + qN_q + 0.4\gamma_b B N_\gamma$.
- **Circular footing** (diameter B): $q_{ult} = 1.3cN_c + qN_q + 0.3\gamma_b B N_\gamma$.

7.2 Allowable Bearing Capacity and Safety Factor

$$q_{allow} = \frac{q_{ult}}{FS} \quad (\text{typically } FS = 3.0)$$

7.3 Eccentric Footing Loading and Base Pressures

When axial vertical force $P = \sum V$ acts with moment M , eccentricity $e = \frac{M}{P}$.

Base Pressure Distribution (FE Handbook 10.6)

$$e = \frac{B}{2} - \frac{\sum M_R - M_O}{\sum V} \implies q_{toe,heel} = \frac{\sum V}{B} \left(1 \pm \frac{6e}{B} \right)$$

The displayed vertical-load/ B term applies to a strip or wall base per unit length. For a rectangular footing, use P/A .

If $e \leq B/6$, the base remains in compression; if $e > B/6$, part of the base loses contact.

8 Foundation Selection and Types

Foundation selection balances structural load requirements against subsurface geotechnical soil profile constraints.

Table 1: **General Foundation Selection Guidance**

Foundation Type	Typical Subsurface Conditions	Application & Key Features
Spread Footings	Firm, dense soil or rock with high bearing capacity with acceptable settlement.	Individual columns for low-to-medium rise residential and commercial buildings. Economical.
Wall Footings	Stable shallow soil layer along structural perimeter.	Continuous concrete strip supporting load-bearing walls or retaining wall bases.
Mat / Raft	Weak/soft cohesive soil where individual footings would cover much of the footprint.	Heavy structure, high column loads; bridges across variable soils to minimize differential settlement.
Deep Piles	Weak upper soils (muck, loose fill, soft clay) overlying dense stratum/rock.	Friction or end-bearing driven piles (steel H-piles, precast concrete) for bridges and high-rises.
Drilled Shafts	Deep competent bearing layer; high lateral/axial load capacity needed.	Large diameter bored piers placed in excavated shafts; used for heavy bridge piers and abutments.

9 Consolidation & Differential Settlement

Consolidation is the time-dependent volumetric strain in saturated fine-grained clay soils resulting from water squeezed out under excess pore pressure.

9.1 Consolidation Parameters and Indices

From 1D consolidation test (e vs. $\log \sigma'$ curve):

Consolidation Indices (FE Handbook 10.6)

$$\text{Compression Index (Virgin Range): } C_c = \frac{\Delta e}{\log(\sigma'_f/\sigma'_0)} \approx 0.009(LL - 10)$$

$$\text{Recompression Index (Overconsolidated Range): } C_r \approx \frac{C_c}{6}$$

9.2 Primary Consolidation Settlement (H) Δ

Let H_0 be initial clay layer thickness, e_0 initial void ratio, σ'_0 initial effective stress, σ'_c preconsolidation pressure, and $\sigma'_f = \sigma'_0 + \Delta\sigma'$ final effective stress.

Settlement Equations (FE Handbook 10.6)

1. Normally Consolidated Clay ($\sigma'_0 \approx \sigma'_c$):

$$\Delta H = \frac{H_0}{1 + e_0} C_c \log \left(\frac{\sigma'_f}{\sigma'_0} \right)$$

2. Overconsolidated Clay — Case 1 ($\sigma'_f \leq \sigma'_c$):

$$\Delta H = \frac{H_0}{1 + e_0} C_r \log \left(\frac{\sigma'_f}{\sigma'_0} \right)$$

3. Overconsolidated Clay — Case 2 ($\sigma'_0 < \sigma'_c < \sigma'_f$):

$$\Delta H = \frac{H_0}{1 + e_0} \left[C_r \log \left(\frac{\sigma'_c}{\sigma'_0} \right) + C_c \log \left(\frac{\sigma'_f}{\sigma'_c} \right) \right]$$

10 Slope Stability Analysis

Slope stability evaluates factor of safety against shear sliding along planar or rotational slip surfaces.

10.1 Planar Slip Surface Model

For soil mass of weight W_M above planar slip surface of length L_S inclined at angle α_S :

Slope Stability Factor of Safety (FE Handbook 10.6)

$$FS = \frac{cbL_S + (W_M \cos \alpha_S - U) \tan \phi}{W_M \sin \alpha_S}$$

b is strip width; U is pore-water force on the slip plane. Dry soil: $U = 0$.

11 Soil Stabilization Methods

Soil stabilization enhances shear strength, reduces compressibility, and improves moisture durability.

- **Mechanical Compaction:** Dynamic compaction, vibratory rolling, sheep-foot compaction.
- **Chemical Admixtures:** Lime treatment (for expansive clay flocculation), Portland Cement (for granular soil hydration), Fly Ash, Bitumen.
- **Geosynthetics:** Geotextiles (separation/filtration), Geogrids (reinforcement for subgrade stabilization), Geomembranes (impermeable barriers).
- *Note:* Site clearing, grubbing, and excavation are site prep actions, NOT stabilization methods.

12 Example Problems and Solutions

Problem 1: USCS Soil Classification

Question: A sand sample with nonplastic silty fines has 100% passing No. 4 and 8% passing No. 200. Laboratory grain-size analysis indicates a uniformity coefficient $C_u = 8.0$ and coefficient of curvature $C_c = 2.5$. Using USCS, what is the proper soil classification?
(A) SW (B) SP (C) SW-SM (D) SP-SM

Solution

Ref: Supplied FE Handbook 10.6, USCS classification.

1. Fines content passing No. 200 is 8% (between 5% and 12%). Dual symbol classification is required.
2. Coarse portion: 100% passes No. 4, so it is Sand (*S*).
3. Gradation criteria for Sand: $C_u \geq 6$ (given $8 \geq 6$) and $1 \leq C_c \leq 3$ (given 2.5). Thus, gradation is Well-Graded (*SW*).
4. Fines portion: Nonplastic silty fines (*SM*). Combining dual symbols yields SW-SM.

Correct Answer: (C)

Problem 2: AASHTO Soil Group Index

Question: A soil has 65% passing the No. 200 sieve, Liquid Limit $LL = 48$, and Plastic Limit $PL = 22$. What is the AASHTO Group Index (GI)?
(A) 5 (B) 9 (C) 11 (D) 15

Solution

Ref: Supplied FE Handbook 10.6, AASHTO group index.

1. Calculate Plasticity Index: $PI = LL - PL = 48 - 22 = 26$.
2. Apply AASHTO GI equation ($F_{200} = 65$):

$$GI = (F_{200} - 35)[0.2 + 0.005(LL - 40)] + 0.01(F_{200} - 15)(PI - 10)$$

$$GI = (65 - 35)[0.2 + 0.005(48 - 40)] + 0.01(65 - 15)(26 - 10)$$

$$GI = 30(0.24) + 0.5(16) = 7.2 + 8.0 = 15.2$$

Rounding to the nearest integer yields $GI = 15$.

Correct Answer: (D)

Problem 3: Sieve Analysis Gradation Coefficients

Question: From a sieve analysis grain-size distribution curve, $D_{10} = 0.15$ mm, $D_{30} = 0.45$ mm, and $D_{60} = 1.35$ mm. Calculate C_u and C_c .

(A) $C_u = 9.0, C_c = 1.0$ (B) $C_u = 9.0, C_c = 2.8$ (C) $C_u = 6.0, C_c = 1.0$ (D) $C_u = 10.0, C_c = 2.5$

Solution

Ref: Supplied FE Handbook 10.6, gradation.

1. Calculate Uniformity Coefficient:

$$C_u = \frac{D_{60}}{D_{10}} = \frac{1.35}{0.15} = 9.0$$

2. Calculate Coefficient of Curvature:

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} = \frac{(0.45)^2}{0.15 \times 1.35} = \frac{0.2025}{0.2025} = 1.0$$

Correct Answer: (A)

Problem 4: Soil Phase Diagram Void Ratio

Question: A moist soil sample has a total volume of 1.24 ft^3 , volume of solids $V_s = 0.82 \text{ ft}^3$, volume of water $V_w = 0.24 \text{ ft}^3$, and volume of air $V_a = 0.18 \text{ ft}^3$. What is the void ratio e ?

(A) 0.34 (B) 0.40 (C) 0.51 (D) 0.62

Solution

Ref: Supplied FE Handbook 10.6, phase relationships.

1. Calculate volume of voids V_v :

$$V_v = V_w + V_a = 0.24 + 0.18 = 0.42 \text{ ft}^3$$

2. Calculate void ratio e :

$$e = \frac{V_v}{V_s} = \frac{0.42}{0.82} = 0.512 \approx 0.51$$

Correct Answer: (C)

Problem 5: Saturated Unit Weight Calculation

Question: A soil sample is fully saturated ($S = 100\%$) with water content $w = 25\%$ and specific gravity of solids $G_s = 2.66$. Calculate its saturated unit weight γ_{sat} in pcf.

(A) 112.6 pcf (B) 124.6 pcf (C) 132.6 pcf (D) 140.2 pcf

Ref: Supplied FE Handbook 10.6, phase relationships.

Ref: NCEES FE Handbook v10.5, pp. 259-260

1. Use Golden Phase Identity $S \cdot e = w \cdot G_s$. Since $S = 1.0$:

$$e = w \cdot G_s = 0.25 \times 2.66 = 0.665$$

2. Calculate saturated unit weight γ_{sat} ($\gamma_w = 62.4$ pcf):

$$\gamma_{\text{sat}} = \frac{G_s + e}{1 + e} \gamma_w = \frac{2.66 + 0.665}{1 + 0.665} (62.4) = \frac{3.325}{1.665} (62.4) = 1.997 \times 62.4 = 124.6 \text{ pcf}$$

Correct Answer: (B)

Problem 6: Relative Density of Granular Soil

Question: Soil testing at a site indicates in-place dry unit weight $\gamma_{d,\text{field}} = 115$ pcf. Laboratory testing determines $\gamma_{d,\text{max}} = 122$ pcf and $\gamma_{d,\text{min}} = 100$ pcf. What is the relative density D_r ?
 (A) 68% (B) 72% (C) 86% (D) 94%

Solution

Ref: Supplied FE Handbook 10.6, relative density.

1. Apply Relative Density formula in unit weight terms:

$$D_r = \left[\frac{\gamma_{d,\text{field}} - \gamma_{d,\text{min}}}{\gamma_{d,\text{max}} - \gamma_{d,\text{min}}} \right] \left[\frac{\gamma_{d,\text{max}}}{\gamma_{d,\text{field}}} \right] \times 100\%$$

2. Substitute given values:

$$D_r = \left[\frac{115 - 100}{122 - 100} \right] \left[\frac{122}{115} \right] \times 100\% = \left[\frac{15}{22} \right] \times [1.0608] \times 100\% = 72.3\% \approx 72\%$$

Correct Answer: (B)

Problem 7: Proctor Compaction Moisture Requirement

Question: A soil fill site requires 10,000 yd³ of compacted soil at a dry unit weight of 112 pcf and optimum water content of 14%. The borrow pit soil has a moisture content of 9%. How many gallons of water must be added?
 (A) 120,000 gal (B) 181,300 gal (C) 215,000 gal (D) 250,000 gal

Solution

Ref: Supplied FE Handbook 10.6, water content.

1. Compute total dry mass required W_s :

$$V_{\text{fill}} = 10,000 \text{ yd}^3 \times 27 \text{ ft}^3/\text{yd}^3 = 270,000 \text{ ft}^3$$

$$W_s = \gamma_d \times V = 112 \text{ pcf} \times 270,000 \text{ ft}^3 = 30,240,000 \text{ lbs}$$

2. Water needed per lb of dry soil $\Delta w = w_{\text{opt}} - w_{\text{borrow}} = 0.14 - 0.09 = 0.05$.
3. Total weight of water added: $W_w = 30,240,000 \times 0.05 = 1,512,000 \text{ lbs}$.
4. Volume of water in gallons (1 gal = 8.34 lbs):

$$V_{\text{water}} = \frac{1,512,000}{8.34} = 181,295 \text{ gal} \approx 181,300 \text{ gal}$$

Correct Answer: (B)

Problem 8: Effective Stress Profile Calculation

Question: A soil profile consists of 6.5 ft of dry sand ($\gamma = 110$ pcf) overlying a thick clay layer ($\gamma_{\text{sat}} = 122$ pcf). The groundwater table is located at 6.5 ft below ground surface. Determine the effective vertical stress σ' at a depth of 11.0 ft.

(A) 715 psf (B) 902 psf (C) 980 psf (D) 1,264 psf

Solution

Ref: Supplied FE Handbook 10.6, effective stress.

1. Depth in upper dry sand layer $h_1 = 6.5$ ft; depth in lower saturated clay $h_2 = 11.0 - 6.5 = 4.5$ ft.
2. Total vertical stress σ :

$$\sigma = (110 \times 6.5) + (122 \times 4.5) = 715 + 549 = 1,264 \text{ psf}$$

3. Pore water pressure u :

$$u = \gamma_w \times h_2 = 62.4 \times 4.5 = 280.8 \text{ psf}$$

4. Effective vertical stress σ' :

$$\sigma' = 1,264 - 280.8 = 983.2 \text{ psf} \approx 980 \text{ psf}$$

Correct Answer: (C)

Problem 9: Effective Stress with Surface Surcharge

Question: A uniform surcharge $S = 400$ psf is applied. The groundwater table is at the ground surface. A saturated soil layer with saturated unit weight $= 125$ pcf extends to 10 ft depth. What is the effective stress at 10 ft?

(A) 626 psf (B) 1,026 psf (C) 1,250 psf (D) 1,650 psf

Solution

Ref: Supplied FE Handbook 10.6, effective stress.

1. Submerged unit weight: $\gamma' = \gamma_{\text{sat}} - \gamma_w = 125 - 62.4 = 62.6$ pcf.
2. Effective stress formula with surcharge:

$$\sigma' = S + \gamma' \cdot h = 400 + (62.6 \times 10) = 400 + 626 = 1,026 \text{ psf}$$

Correct Answer: (B)

Problem 10: Active Earth Pressure Resultant Force

Question: A retaining wall holds an 8.0 ft high vertical face of dry sand backfill ($\gamma = 115$ pcf, $\phi = 32^\circ$, $c = 0$). Compute the total horizontal Rankine active force P_A per linear foot of wall.

(A) 1,130 lb/ft (B) 2,040 lb/ft (C) 2,250 lb/ft (D) 3,680 lb/ft

Solution

Ref: Supplied FE Handbook 10.6, earth pressure.

1. Rankine active pressure coefficient K_a :

$$K_a = \tan^2 \left(45^\circ - \frac{32^\circ}{2} \right) = \tan^2(29^\circ) = (0.5543)^2 = 0.3073$$

2. Active force resultant P_A :

$$P_A = \frac{1}{2} K_a \gamma H^2 = \frac{1}{2} (0.3073)(115)(8.0)^2 = 0.5 \times 0.3073 \times 115 \times 64 = 1,130.8 \text{ lb/ft} \approx 1,130 \text{ lb/ft}$$

Correct Answer: (A)

Problem 11: Passive Earth Pressure Force

Question: A toe wall embedment provides passive resistance in sand backfill ($\gamma = 120$ pcf, $\phi = 30^\circ$, $c = 0$) over a depth of 4.0 ft. Calculate the total passive resistance force P_P per linear foot.
 (A) 960 lb/ft (B) 1,440 lb/ft (C) 2,880 lb/ft (D) 5,760 lb/ft

Solution

Ref: Supplied FE Handbook 10.6, earth pressure.

1. Rankine passive pressure coefficient K_p :

$$K_p = \tan^2 \left(45^\circ + \frac{30^\circ}{2} \right) = \tan^2(60^\circ) = 3.0$$

2. Passive force resultant P_P :

$$P_P = \frac{1}{2} K_p \gamma H^2 = \frac{1}{2} (3.0) (120) (4.0)^2 = 1.5 \times 120 \times 16 = 2,880 \text{ lb/ft}$$

Correct Answer: (C)

Problem 12: Mohr-Coulomb Shear Strength

Question: A direct shear test on a clayey sand yields cohesion $c = 300$ psf and internal friction angle $\phi = 25^\circ$. What is the shear strength τ_F on a plane subjected to a normal stress $\sigma_N = 1,200$ psf?
 (A) 510 psf (B) 860 psf (C) 900 psf (D) 1,120 psf

Solution

Ref: Supplied FE Handbook 10.6, shear strength.

1. Apply Mohr-Coulomb failure criterion:

$$\tau_F = c + \sigma_N \tan \phi$$

2. Substitute values:

$$\tau_F = 300 + 1,200 \tan(25^\circ) = 300 + 1,200(0.4663) = 300 + 559.6 = 859.6 \approx 860 \text{ psf}$$

Correct Answer: (B)

Problem 13: Triaxial Compression Test Friction Angle

Question: A poorly graded sand sample ($c = 0$) subjected to a triaxial test under a confining pressure $\sigma_3 = 10$ psi fails at a major principal stress $\sigma_1 = 34$ psi. Calculate the internal friction angle ϕ .
 (A) 28° (B) 31° (C) 33° (D) 38°

Solution

Ref: Supplied FE Handbook 10.6, shear strength.

1. For cohesionless soil ($c = 0$), triaxial principal stress ratio relates to friction angle by:

$$\sin \phi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3}$$

2. Substitute stress values:

$$\sin \phi = \frac{34 - 10}{34 + 10} = \frac{24}{44} = 0.5455$$

3. Solve for ϕ :

$$\phi = \arcsin(0.5455) = 33.06^\circ \approx 33^\circ$$

Correct Answer: (C)

Problem 14: Terzaghi Shallow Footing Bearing Capacity

Question: A continuous strip footing of width $B = 4.0$ ft is founded at depth $D_f = 3.0$ ft in soil with $c = 200$ psf, $\gamma = 115$ pcf, and bearing capacity factors $N_c = 17.7$, $N_q = 7.4$, $N_\gamma = 5.0$. Compute ultimate bearing capacity q_{ult} .
 (A) 4,200 psf (B) 6,093 psf (C) 7,240 psf (D) 8,150 psf

Solution

Ref: Supplied FE Handbook 10.6, bearing capacity.

1. Apply the Terzaghi strip-footing equation using effective unit weight = 115 pcf:

$$q_{ult} = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma$$

2. Substitute parameters:

$$q_{ult} = (200 \times 17.7) + (115 \times 3.0 \times 7.4) + (0.5 \times 115 \times 4.0 \times 5.0)$$

$$q_{ult} = 3,540 + 2,553 + 1,150 = 7,243 \text{ psf} \approx 7,240 \text{ psf}$$

Correct Answer: (C)

Problem 15: Footing Base Pressure with Load Eccentricity

Question: A square footing ($5.0 \text{ ft} \times 5.0 \text{ ft}$) carries a vertical axial load $P = 80$ kips and a moment $M = 20$ kip-ft. Determine the maximum toe pressure q_{toe} .
 (A) 3.20 ksf (B) 4.16 ksf (C) 5.12 ksf (D) 6.40 ksf

Solution

Ref: Supplied FE Handbook 10.6, eccentric foundations.

1. Calculate load eccentricity e :

$$e = \frac{M}{P} = \frac{20 \text{ kip-ft}}{80 \text{ kips}} = 0.25 \text{ ft}$$

2. Check Middle Third Rule: $B/6 = 5.0/6 = 0.833$ ft. Since $e = 0.25 < 0.833$, base is fully in compression.
3. Calculate maximum base pressure q_{toe} :

$$q_{toe} = \frac{P}{B^2} \left(1 + \frac{6e}{B} \right) = \frac{80}{25} \left(1 + \frac{6(0.25)}{5.0} \right) = 3.2(1 + 0.30) = 3.2 \times 1.30 = 4.16 \text{ ksf}$$

Correct Answer: (B)

Problem 16: Foundation Type Selection

Question: A bridge abutment is located adjacent to a river channel. Subsurface boring reveals 35 ft of soft, highly compressible organic muck ($q_{allow} < 500$ psf) overlying solid limestone bedrock. Which foundation system is most appropriate?
 (A) Shallow spread footings (B) Continuous wall footings (C) Mat foundation (D) Driven steel H-piles to bedrock

Solution

Ref: Supplied FE Handbook 10.6, FE Civil topic specification.

1. Weak organic muck layer cannot support shallow footings or mat foundation without excessive settlement.
2. Solid limestone bedrock at 35 ft depth provides excellent end-bearing capacity.

3. Deep foundations (piles driven to bedrock) bypass weak surface soil and transmit structural loads directly to rock.

Correct Answer: (D)

Problem 17: Consolidation Index Empirical Estimates

Question: A clay soil has Plasticity Index $PI = 40$ and Plastic Limit $PL = 30$. Estimate its compression index C_c and recompression index C_r .

(A) $C_c = 0.54, C_r = 0.09$ (B) $C_c = 0.36, C_r = 0.06$ (C) $C_c = 0.45, C_r = 0.12$ (D) $C_c = 0.63, C_r = 0.10$

Solution

Ref: Supplied FE Handbook 10.6, consolidation.

1. Calculate Liquid Limit LL : $LL = PL + PI = 30 + 40 = 70$.

2. Terzaghi correlation for Compression Index C_c :

$$C_c \approx 0.009(LL - 10) = 0.009(70 - 10) = 0.009(60) = 0.54$$

3. Empirical correlation for Recompression Index C_r :

$$C_r \approx \frac{C_c}{6} = \frac{0.54}{6} = 0.09$$

Correct Answer: (A)

Problem 18: Primary Consolidation Settlement of Overconsolidated Clay

Question: A 2.0 m thick clay layer ($e_0 = 1.5, C_c = 0.30, C_r = 0.05$) has an initial overburden pressure $\sigma'_0 = 50$ kPa at mid-depth. Preconsolidation pressure $\sigma'_c = 74$ kPa. Construction increases vertical stress by $\Delta\sigma' = 34$ kPa (so final stress $\sigma'_f = 84$ kPa). Calculate primary consolidation settlement ΔH in cm.

(A) 0.9 cm (B) 1.5 cm (C) 2.0 cm (D) 5.4 cm

Solution

Ref: Supplied FE Handbook 10.6, consolidation.

1. Check stress ranges: $\sigma'_0 = 50$ kPa $<$ $\sigma'_c = 74$ kPa $<$ $\sigma'_f = 84$ kPa.

2. Apply Case 2 Overconsolidated Clay Settlement Formula:

$$\Delta H = \frac{H_0}{1 + e_0} \left[C_r \log \left(\frac{\sigma'_c}{\sigma'_0} \right) + C_c \log \left(\frac{\sigma'_f}{\sigma'_c} \right) \right]$$

3. Calculate log terms:

$$\log(74/50) = \log(1.48) = 0.1703$$

$$\log(84/74) = \log(1.1351) = 0.0550$$

4. Substitute values ($H_0 = 200$ cm):

$$\Delta H = \frac{200}{1 + 1.5} [0.05(0.1703) + 0.30(0.0550)] = 80[0.008515 + 0.01650] = 80[0.025015] = 2.001 \text{ cm} \approx 2.0 \text{ cm}$$

Correct Answer: (C)

Problem 19: Slope Stability Factor of Safety

Analyze a **one-foot-wide dry strip**, with $W_M = 60,000$ lb and no pore-water force. Its planar slip surface has $L_s = 75$ ft and $\alpha = 30^\circ$; $c = 216$ psf and $\phi = 21^\circ$. Find the slope safety factor.

- (A) 0.85 (B) 1.02 (C) 1.20 (D) 1.47

Solution

Ref: Supplied FE Handbook 10.6, slope stability.

1. Given cohesion $c = 216$ psf (equivalent to 1.50 psi).
2. Mobilized driving force T_{MOB} :

$$T_{MOB} = W_M \sin \alpha_S = 60,000 \sin(30^\circ) = 30,000 \text{ lbs}$$

3. Available shear resistance force T_{FF} :

$$T_{FF} = cL_S + W_M \cos \alpha_S \tan \phi$$

$$T_{FF} = (216 \times 75) + (60,000 \cos(30^\circ) \tan(21^\circ))$$

$$T_{FF} = 16,200 + (60,000 \times 0.8660 \times 0.3839) = 16,200 + 19,947 = 36,147 \text{ lbs}$$

4. Calculate Factor of Safety FS :

$$FS = \frac{T_{FF}}{T_{MOB}} = \frac{36,147}{30,000} = 1.205 \approx 1.20$$

Correct Answer: (C)

Problem 20: Soil Stabilization Principles

Question: Soil stabilization techniques are designed to improve engineering performance of subgrade soils. Which of the following is NOT recognized as a soil stabilization technique?

- (A) Mechanical compaction using vibratory rollers
- (B) Mixing chemical admixtures such as hydrated lime or fly ash
- (C) Installation of woven geotextiles
- (D) Clearing, grubbing, and mass excavation

Solution

Ref: Supplied FE Handbook 10.6, FE Civil topic specification.

1. Mechanical compaction increases dry unit weight and shear strength.
2. Chemical admixtures (lime, fly ash, cement) modify soil plasticity and induce pozzolanic bonding.
3. Geosynthetics (geotextiles, geogrids) provide subgrade reinforcement and load distribution.
4. Clearing, grubbing, and excavation are earthwork site preparation operations, NOT soil stabilization techniques.

Correct Answer: (D)