

BELLTES ACADEMY

GEOTECHNICAL ENGINEERING

Master Academic Textbook & Field Guide

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Chapter 1: Phase Relationships and Soil Index Properties

Soil is a multi-phase system consisting of solid mineral grains, water, and air. Understanding the spatial and mass ratios among these components is fundamental to all engineering analyses. Key volumetric relationships include void ratio (e), porosity (n), and degree of saturation (S). Mass-volume links are unified by water content (w) and specific gravity of solids (G_s).

$$\begin{aligned} S * e &= w * G_s \\ n &= e / (1 + e) \\ \gamma_d &= \gamma_b / (1 + w) \end{aligned}$$

Chapter 2: Soil Classification Systems (USCS and AASHTO)

Engineering performance is highly correlated with particle size distribution and plastic properties. Atterberg limits define the boundaries of structural phases for fine-grained materials: Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI). The Unified Soil Classification System (USCS) categorizes soils into coarse-grained and fine-grained categories, while AASHTO optimizes classifications for highway subgrades.

$$\begin{aligned} PI &= LL - PL \\ Cu &= D_{60} / D_{10} \\ Cc &= (D_{30})^2 / (D_{10} * D_{60}) \end{aligned}$$

Chapter 3: Soil Compaction Mechanics and Mechanics of Earthworks

Compaction is the mechanical densification of soil by expelling air voids, increasing dry density and structural shear strength. The relationship between dry density and moisture content reveals an Optimum Moisture Content (OMC) at Maximum Dry Density (MDD). Field compliance checks use standard sand-cone replacement and nuclear densitometer methods.

$$\begin{aligned} \gamma_d &= G_s * \gamma_w / (1 + e) \\ \text{Relative Compaction} &= (\gamma_{d_field} / \gamma_{d_max_lab}) * 100 \end{aligned}$$

Chapter 4: Permeability, Hydraulic Conductivity, and Fluid Flow

Permeability is the property of soil allowing fluid transport through interconnected porous networks. Flow through porous media is strictly governed by Darcy's Law, applicable under laminar flow regimes.

Hydraulic conductivity (k) varies drastically between highly permeable gravels and low-permeability clays, influenced by structural arrangement and fluid viscosity.

$$\begin{aligned}v &= k * i \\q &= k * i * A \\i &= \Delta h / L\end{aligned}$$

Chapter 5: Effective Stress Principle and Capillary Phenomena

The behavior of soil under stress is fundamentally governed by the principle of effective stress formulated by Karl Terzaghi. Total stress acting on any plane is the sum of intergranular effective stress and pore water pressure. Capillary action creates negative pore water pressure zones above the phreatic surface, temporarily increasing effective tension and cohesion.

$$\begin{aligned}\sigma &= \sigma_{\text{prime}} + u \\ \sigma_{\text{prime}} &= \sigma - u \\ h_c &= 4 * T_s / (d * \gamma_w)\end{aligned}$$

Chapter 6: Two-Dimensional Seepage and Flow Net Architecture

Two-dimensional fluid seepage through isotropic and anisotropic soil foundations is mathematically governed by Laplace's continuity equation. Flow nets, composed of orthogonal flow lines and equipotential lines, enable graphical solutions to complex boundary conditions. They facilitate exact calculations of seepage discharge, pore pressures, and local hydraulic exit gradients.

$$\begin{aligned}q &= k * H * (N_f / N_d) \\ i_{\text{exit}} &= \Delta h_{\text{min}} / l_{\text{element}} \\ i_{\text{cr}} &= (G_s - 1) / (1 + e)\end{aligned}$$

Chapter 7: Stresses in Soil Mass: Boussinesq and Westergaard Models

External structural loads transmit structural stresses deep into the underlying earth mass. Boussinesq's model solves for stress distributions caused by point, line, and area loads on a semi-infinite, homogenous, isotropic, linear-elastic medium. Westergaard's alternative framework models stratified soil foundations using horizontal inextensible reinforcing elements.

$$\begin{aligned}\Delta \sigma_z &= \left(\frac{3 * P}{2 * \pi * z^2} \right) * \left[\frac{1}{1 + (r/z)^2} \right]^{5/2} \\ \Delta \sigma_z &= q * I_z\end{aligned}$$

Chapter 8: Compressibility and Terzaghi's One-Dimensional Consolidation Theory

Consolidation is the time-dependent expulsion of pore water from saturated, low-permeability clay layers subject to static load overcharging. Terzaghi's classical consolidation equation utilizes the coefficient of consolidation (C_v) and consolidation time factor (T_v) to determine secondary and primary settlement rates over extended asset lifetimes.

$$\begin{aligned}S_c &= \left[\frac{C_c * H_0}{1 + e_0} \right] * \log_{10} \left(\frac{\sigma_0' + \Delta \sigma}{\sigma_0'} \right) \\ T_v &= \frac{C_v * t}{d^2} \\ U &= 1 - \exp(-M^2 * T_v)\end{aligned}$$

Chapter 9: Shear Strength of Soils and Mohr-Coulomb Failure Criteria

The ultimate internal bearing capability of soil is governed completely by its shear capacity. The classical Mohr-Coulomb failure envelope establishes maximum shear capacity as a function of intrinsic cohesion (c) and the internal angle of friction. Effective stress parameters control long-term failure states, while total stress parameters apply to rapid loading scenarios.

$$\begin{aligned}\tau_f &= c' + \sigma' * \tan(\phi') \\ \sigma_1 &= \sigma_3 * \tan^2(45 + \phi/2) + 2 * c * \tan(45 + \phi/2)\end{aligned}$$

Chapter 10: Laboratory and In-Situ Shear Testing Methodology

Accurate parameter derivation requires high-fidelity laboratory testing profiles alongside in-situ logging verification. Lab testing includes Direct Shear tests, and unconfined compression tests, alongside consolidated-drained (CD), consolidated-undrained (CU), and undrained-unconsolidated (UU) Triaxial testing. Field assessments use Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT).

$$N_{corrected} = N_{field} * C_N * C_E * C_B * C_R$$
$$q_u = 2 * s_u$$

Chapter 11: Lateral Earth Pressure: Rankine's Analytical Formulation

Retaining wall evaluations require reliable lateral earth stress calculations. Rankine's analytical formulations assume a smooth, vertical wall interface acting on a soil mass in a state of plastic equilibrium. Formulas define coefficients for active and passive states, yielding linear triangular stress distributions across deep structural vertical planes.

$$K_a = \tan^2(45 - \phi/2) = (1 - \sin(\phi)) / (1 + \sin(\phi))$$
$$K_p = \tan^2(45 + \phi/2) = (1 + \sin(\phi)) / (1 - \sin(\phi))$$
$$p_a = K_a * \sigma_v - 2 * c * \sqrt{K_a}$$

Chapter 12: Lateral Earth Pressure: Coulomb's Wedge Framework

Unlike Rankine, Coulomb's wedge framework accommodates structural wall friction, sloping backfills, and non-vertical retaining surfaces. It approaches lateral earth pressure as a solid boundary-equilibrium problem, where a sliding soil wedge shears along a critical failure plane, optimizing maximum driving or minimum resisting forces.

$$P_a = 0.5 * \gamma * H^2 * K_{a_coulomb}$$
$$K_{a_coulomb} = f(\phi, \beta, \alpha, \delta)$$

Chapter 13: Stability Analysis of Earth Retaining Structures

Rigid, flexible, and mechanically stabilized earth (MSE) retaining structures require comprehensive stability evaluations. External stability checks require verifying safety factors against horizontal sliding along the base, overturning moments about the toe, and foundation bearing capacity failure.

$$\begin{aligned}FS_{sliding} &= (\text{Sum_Horizontal_Resisting_Forces}) / (\text{Sum_Horizontal_Driving_Forces}) \\FS_{overturning} &= (\text{Sum_Resisting_Moments}) / (\text{Sum_Overturning_Moments}) \\e_{centricity} &= (B / 2) - (M_{net} / R_{vertical})\end{aligned}$$

Chapter 14: Bearing Capacity of Shallow Foundations: Terzaghi Formulation

Shallow foundations (spread and mat footprints) must support structures without undergoing shear failure or excessive settlement. Terzaghi's bearing capacity equation accounts for cohesive strength, surcharge confinement, and soil self-weight using dimensionless capacity factors dependent purely on the soil friction angle.

$$\begin{aligned}q_{ult} &= c * N_c * s_c + q * N_q + 0.5 * \gamma * B * N_\gamma * s_\gamma \\q_{allowable} &= q_{ult} / FS\end{aligned}$$

Chapter 15: Deep Foundations: Pile Bearing Capacity and Skin Friction Mechanics

When shallow deposits lack sufficient stiffness, structural loads are transferred to deeper strata via pile elements or drilled shafts. Total axial capacity is derived from the summation of end-bearing resistance at the pile tip and side shear/skin friction resistance generated along the structural shaft perimeter.

$$\begin{aligned}Q_{ult} &= Q_p + Q_s \\Q_p &= q_p * A_p = (c * N_c + q_{prime} * N_q) * A_p \\Q_s &= \text{Sum}(f_i * A_{s_i})\end{aligned}$$

Chapter 16: Settlement Analysis of Shallow and Deep Foundations

Total foundation movement comprises immediate elastic settlement, primary consolidation settlement, and secondary creep. Elastic deflection calculations use elastic modulus (E_s) values and influence elements dependent on foundation geometry and structural rigidity boundaries.

$$S_{\text{elastic}} = q * B * ((1 - \nu_s^2) / E_s) * I_p$$
$$S_{\text{total}} = S_{\text{elastic}} + S_{\text{consolidation}} + S_{\text{secondary}}$$

Chapter 17: Stability Analysis of Infinite and Finite Slopes

Slope stability evaluations assess the safety factor of soil slopes against sliding along potential failure surfaces. Infinite slope equations apply to shallow, elongated failure planes, while finite slope dynamics require advanced Bishop, Janbu, or Morgenstern-Price methods of slices to determine critical circular failure boundaries.

$$FS_{\text{infinite}} = (c_{\text{prime}} / (\gamma * z * \sin(\beta) * \cos(\beta))) + (\tan(\phi_{\text{prime}}) / \tan(\beta))$$
$$FS_{\text{slices}} = \text{Sum}(\text{Resisting_Moments}) / \text{Sum}(\text{Driving_Moments})$$

Chapter 18: Soil Stabilization, Ground Improvement, and Geosynthetics

Deficient marginal sites often require engineering modifications to meet mechanical performance specifications. Improvement strategies include physical dynamic compaction, deep stone column installation, chemical cementitious stabilization, and the integration of polymeric geosynthetics (geotextiles, geogrids) for reinforcement.

$$\text{Bearing_Capacity_Enhanced} = \text{Bearing_Capacity_Raw} * \text{Factor_Improvement}$$
$$T_{\text{allowable}} = T_{\text{ult}} / (RF_{\text{ID}} * RF_{\text{CR}} * RF_{\text{CBD}})$$

Chapter 19: Subsurface Geotechnical Exploration and Site Investigation

Subsurface explorations manage site uncertainty and mitigate foundation risks. Comprehensive site campaigns comprise boring profiles, high-fidelity Shelby tube core extraction, rock quality designation (RQD) index testing, and cross-borehole geophysical imaging arrays.

$$\begin{aligned} \text{RQD} &= (\text{Sum_Length_Core_Pieces_Greater_Than_10cm} / \\ &\quad \text{Total_Core_Run_Length}) * 100 \\ \text{Recovery_Ratio} &= (\text{Length_Core_Recovered} / \text{Total_Core_Advanced}) * 100 \end{aligned}$$

Chapter 20: Advanced Computational Geotechnics and Finite Element Modeling

Modern geotechnical analysis resolves complex boundary arrays using finite element modeling (FEM). Soil behavior is simulated via advanced constitutive models including linear-elastic, Mohr-Coulomb plastic, Cam-Clay hardening, and soft-soil models to capture true non-linear stress-strain trajectories.

$$\begin{aligned} [\mathbf{K_global}] * \{\mathbf{U_displacement}\} &= \{\mathbf{F_external}\} \\ f(\sigma_{ij}, \text{engineering_parameters}) &= 0 \end{aligned}$$