

2E  
2ND EDITION

# SOIL MECHANICS AND FOUNDATIONS

MUNI BUDHU



# CONTENTS

PREFACE **iii**

NOTES FOR STUDENTS AND INSTRUCTORS **vi**

NOTES FOR INSTRUCTORS **xi**

## CHAPTER 1 INTRODUCTION TO SOIL MECHANICS AND FOUNDATIONS **1**

- 1.0 Introduction **1**
- 1.1 Marvels of Civil Engineering—The Hidden Truth **2**
- 1.2 Geotechnical Lessons from Failures **4**

## CHAPTER 2 GEOLOGICAL CHARACTERISTICS OF SOILS AND SOILS INVESTIGATION **6**

- 2.0 Introduction **6**
- 2.1 Definitions of Key Terms **6**
- 2.2 Questions to Guide Your Reading **7**
- 2.3 Basic Geology **7**
  - 2.3.1 Importance of Geology **7**
  - 2.3.2 Earth's Profile **8**
  - 2.3.3 Plate Tectonics **8**
  - 2.3.4 Composition of Earth's Crust **9**
  - 2.3.5 Discontinuities **9**
  - 2.3.6 Geologic Cycle and Geological Time **10**
- 2.4 Composition of Soils **12**
  - 2.4.1 Soil Formation **12**
  - 2.4.2 Soil Types **12**
  - 2.4.3 Clay Minerals **13**
  - 2.4.4 Surface Forces and Adsorbed Water **15**
  - 2.4.5 Soil Fabric **15**
  - 2.4.6 Comparison of Coarse-Grained and Fine-Grained Soils for Engineering Use **17**
- 2.5 Soils Investigation **18**
  - 2.5.1 Purposes of a Soils Investigation **18**
  - 2.5.2 Phases of a Soils Investigation **18**
- 2.6 Soils Exploration Program **19**
  - 2.6.1 Soil Exploration Methods **19**
  - 2.6.2 Soil Identification in the Field **20**
  - 2.6.3 Depth of Boreholes **22**
  - 2.6.4 Soil Sampling **22**

- 2.6.5 Groundwater Conditions **23**
- 2.6.6 Soils Laboratory Tests **23**
- 2.6.7 In Situ or Field Tests **23**
- 2.6.8 Boring Log **29**

- 2.7 Summary **30**
- Exercises **30**

## CHAPTER 3 PHYSICAL SOIL PARAMETERS **32**

- 3.0 Introduction **32**
- 3.1 Definitions of Key Terms **32**
- 3.2 Questions to Guide Your Reading **33**
- 3.3 Phase Relationships **34**
- 3.4 Determination of Particle Size of Soils **42**
  - 3.4.1 Particle Size of Coarse-Grained Soils **42**
  - 3.4.2 Particle Size of Fine-Grained Soils **43**
  - 3.4.3 Characterization of Soils Based on Particle Size **44**
- 3.5 Physical States and Index Properties of Fine-Grained Soils **48**
- 3.6 Determination of the Liquid, Plastic, and Shrinkage Limits **50**
  - 3.6.1 Casagrande Cup Method **50**
  - 3.6.2 Plastic Limit Test **51**
  - 3.6.3 Fall Cone Method to Determine Liquid and Plastic Limits **51**
  - 3.6.4 Shrinkage Limit **52**
- 3.7 Soil Classification Schemes **55**
- 3.8 Engineering Use Chart **60**
- 3.9 Dry Unit Weight–Water Content Relationship **64**
  - 3.9.1 Basic Concept **64**
  - 3.9.2 Proctor Compaction Test **64**
  - 3.9.3 Zero Air Voids Curve **66**
  - 3.9.4 Importance of Compaction **66**
  - 3.9.5 Field Compaction **67**
  - 3.9.6 Compaction Quality Control **67**
    - 3.9.6.1 Sand Cone **67**
    - 3.9.6.2 Balloon Test **68**
    - 3.9.6.3 Nuclear Density Meter **69**
- 3.10 Summary **72**
- Practical Examples **72**
- Exercises **74**

**CHAPTER 4 ONE-DIMENSIONAL FLOW OF WATER THROUGH SOILS 78**

- 4.0 Introduction **78**
- 4.1 Definitions of Key Terms **78**
- 4.2 Questions to Guide Your Reading **78**
- 4.3 Groundwater **79**
- 4.4 Head **79**
- 4.5 Darcy's Law **81**
- 4.6 Empirical Relationships for  $k$  **83**
- 4.7 Flow Parallel to Soil Layers **87**
- 4.8 Flow Normal to Soil Layers **88**
- 4.9 Equivalent Hydraulic Conductivity **89**
- 4.10 Determination of the Hydraulic Conductivity **90**
  - 4.10.1 Constant-Head Test **90**
  - 4.10.2 Falling-Head Test **91**
  - 4.10.3 Pumping Test to Determine the Hydraulic Conductivity **94**
- 4.11 Groundwater Lowering by Wellpoints **96**
- 4.12 Summary **98**
  - Practical Example **98**
  - Exercises **99**

**CHAPTER 5 STRESSES, STRAINS, AND ELASTIC DEFORMATIONS OF SOILS 103**

- 5.0 Introduction **103**
- 5.1 Definitions of Key Terms **104**
- 5.2 Questions to Guide Your Reading **105**
- 5.3 Stresses and Strains **105**
  - 5.3.1 Normal Stresses and Strains **106**
  - 5.3.2 Volumetric strain **106**
  - 5.3.3 Shear Stresses and Shear Strains **106**
- 5.4 Idealized Stress–Strain Response and Yielding **107**
  - 5.4.1 Material Responses to Normal Loading and Unloading **107**
  - 5.4.2 Material Response to Shear Forces **109**
  - 5.4.3 Yield Surface **110**
- 5.5 Hooke's Law **111**
  - 5.5.1 General State of Stress **111**
  - 5.5.2 Principal Stresses **112**
  - 5.5.3 Displacements from Strains and Forces from Stresses **112**
- 5.6 Plane Strain and Axial Symmetric Conditions **113**
  - 5.6.1 Plane Strain Condition **113**
  - 5.6.2 Axisymmetric Condition **114**
- 5.7 Anisotropic Elastic States **116**
- 5.8 Stress and Strain States **118**
  - 5.8.1 Mohr's Circle for Stress States **119**
  - 5.8.2 Mohr's Circle for Strain States **120**
- 5.9 Total and Effective Stresses **123**

- 5.9.1 The Principle of Effective Stress **123**
- 5.9.2 Effective Stresses Due to Geostatic Stress Fields **125**
- 5.9.3 Effects of Capillarity **126**
- 5.9.4 Effects of Seepage **127**
- 5.10 Lateral Earth Pressure at Rest **131**
- 5.11 Stresses in Soil from Surface Loads **133**
  - 5.11.1 Point Load **134**
  - 5.11.2 Line Load **135**
  - 5.11.3 Line Load Near a Buried Earth Retaining Structure **136**
  - 5.11.4 Strip Load **136**
  - 5.11.5 Uniformly Loaded Circular Area **138**
  - 5.11.6 Uniformly Loaded Rectangular Area **138**
  - 5.11.7 Approximate Method for Rectangular Loads **140**
  - 5.11.8 Vertical Stress Below Arbitrarily Shaped Area **142**
- 5.12 Stress and Strain Invariants **147**
  - 5.12.1 Mean Stress **147**
  - 5.12.2 Deviatoric or Shear Stress **147**
  - 5.12.3 Volumetric Strain **147**
  - 5.12.4 Deviatoric or Distortional or Shear Strain **148**
  - 5.12.5 Axisymmetric Condition **148**
  - 5.12.6 Plane Strain **148**
  - 5.12.7 Hooke's Law Using Stress and Strain Invariants **149**
- 5.13 Stress Paths **152**
  - 5.13.1 Basic Concept **152**
  - 5.13.2 Plotting Stress Paths **153**
  - 5.13.3 Procedure For Plotting Stress Paths **157**
- 5.14 Summary **159**
  - Practical Example **160**
  - Exercises **161**

**CHAPTER 6 ONE-DIMENSIONAL CONSOLIDATION SETTLEMENT OF FINE-GRAINED SOILS 166**

- 6.0 Introduction **166**
- 6.1 Definitions of Key Terms **167**
- 6.2 Questions to Guide Your Reading **168**
- 6.3 Basic Concepts **168**
  - 6.3.1 Instantaneous Load **169**
  - 6.3.2 Consolidation Under a Constant Load—Primary Consolidation **170**
  - 6.3.3 Secondary Compression **171**
  - 6.3.4 Drainage Path **171**
  - 6.3.5 Rate of Consolidation **171**
  - 6.3.6 Effective Stress Changes **171**
  - 6.3.7 Void Ratio and Settlement Changes Under a Constant Load **172**

- 6.3.8 Effects of Vertical Stresses on Primary Consolidation **172**
  - 6.3.9 Primary Consolidation Parameters **173**
  - 6.3.10 Effects of Loading History **174**
  - 6.3.11 Overconsolidation Ratio **175**
  - 6.3.12 Possible and Impossible Consolidation Soil States **175**
  - 6.4 Calculation of Primary Consolidation Settlement **176**
    - 6.4.1 Effects of Unloading/Reloading of a Soil Sample Taken from the Field **176**
    - 6.4.2 Primary Consolidation Settlement of Normally Consolidated Fine-Grained Soils **177**
    - 6.4.3 Primary Consolidation Settlement of Overconsolidated Fine-Grained Soils **177**
    - 6.4.4 Procedure to Calculate Primary Consolidation Settlement **178**
    - 6.4.5 Thick Soil Layers **178**
  - 6.5 One-Dimensional Consolidation Theory **184**
    - 6.5.1 Derivation of Governing Equation **185**
    - 6.5.2 Solution of Governing Consolidation Equation Using Fourier Series **187**
    - 6.5.3 Finite Difference Solution of the Governing Consolidation Equation **189**
  - 6.6 Secondary Compression Settlement **194**
  - 6.7 One-Dimensional Consolidation Laboratory Test **195**
    - 6.7.1 Oedometer Test **195**
    - 6.7.2 Determination of the Coefficient of Consolidation **196**
      - 6.7.2.1 Root Time Method **196**
      - 6.7.2.2 Log Time Method **197**
    - 6.7.3 Determination of Void Ratio at the End of a Loading Step **198**
    - 6.7.4 Determination of the Preconsolidation Effective Stress **199**
    - 6.7.5 Determination of Compression and Recompression Indices **200**
    - 6.7.6 Determination of the Modulus of Volume Change **200**
    - 6.7.7 Determination of the Secondary Compression Index **201**
  - 6.8 Relationship Between Laboratory and Field Consolidation **204**
  - 6.9 Typical Values of Consolidation Settlement Parameters and Empirical Relationships **205**
  - 6.10 Preconsolidation of Soils Using Wick Drains **206**
  - 6.11 Summary **209**
    - Practical Examples **210**
    - Exercises **216**
- CHAPTER 7 SHEAR STRENGTH OF SOILS 221**
- 7.0 Introduction **221**
  - 7.1 Definitions of Key Terms **221**
  - 7.2 Questions to Guide Your Reading **222**
  - 7.3 Typical Response of Soils to Shearing Forces **223**
    - 7.3.1 Effects of Increasing the Normal Effective Stress **225**
    - 7.3.2 Effects of Overconsolidation Ratio **226**
    - 7.3.3 Cemented Soils **227**
    - 7.3.4 Unsaturated Soils **227**
  - 7.4 Two Simple Models for the Shear Strength of Soils **228**
    - 7.4.1 Coulomb's Model **228**
    - 7.4.2 Taylor's Model **232**
  - 7.5 Interpretation of the Shear Strength of Soils **233**
  - 7.6 Mohr–Coulomb Failure Criterion **237**
  - 7.7 Practical Implications of Coulomb and Mohr–Coulomb Failure Criteria **241**
  - 7.8 Undrained and Drained Shear Strength **243**
  - 7.9 Laboratory Tests to Determine Shear Strength Parameters **245**
    - 7.9.1 A Simple Test to Determine Friction Angle of Clean Coarse-Grained Soils **245**
    - 7.9.2 Shear Box or Direct Shear Test **246**
    - 7.9.3 Conventional Triaxial Apparatus **251**
    - 7.9.4 Unconfined Compression (UC) Test **253**
    - 7.9.5 Consolidated Drained (CD) Compression Test **255**
    - 7.9.6 Consolidated Undrained (CU) Compression Test **260**
    - 7.9.7 Unconsolidated Undrained (UU) Test **263**
  - 7.10 Porewater Pressure under Axisymmetric Undrained Loading **265**
  - 7.11 Other Laboratory Devices to Measure Shear Strength **266**
    - 7.11.1 Simple Shear Apparatuses **267**
    - 7.11.2 True Triaxial Apparatus **271**
    - 7.11.3 Hollow Cylinder Apparatus **271**
  - 7.12 Field Tests **272**
    - 7.12.1 Vane Shear Test (VST) **272**
    - 7.12.2 The Standard Penetration Test (SPT) **272**
    - 7.12.3 Cone Penetrometer Test (CPT) **273**

- 7.13 Empirical Relationships for Shear Strength Parameters **274**
- 7.14 Summary **274**  
Practical Examples **275**  
Exercises **278**

## **CHAPTER 8** *A CRITICAL STATE MODEL TO INTERPRET SOIL BEHAVIOR* **284**

- 8.0 Introduction **284**
- 8.1 Definitions of Key Terms **285**
- 8.2 Questions to Guide Your Reading **285**
- 8.3 Basic Concepts **286**
  - 8.3.1 Parameter Mapping **286**
  - 8.3.2 Failure Surface **287**
  - 8.3.3 Soil Yielding **288**
  - 8.3.4 Prediction of the Behavior of Normally Consolidated and Lightly Overconsolidated Soils Under Drained Conditions **289**
  - 8.3.5 Prediction of the Behavior of Normally Consolidated and Lightly Overconsolidated Soils Under Undrained Conditions **290**
  - 8.3.6 Prediction of the Behavior of Heavily Overconsolidated Soils **291**
  - 8.3.7 Critical State Boundary **292**
  - 8.3.8 Volume Changes and Excess Porewater Pressures **293**
  - 8.3.9 Effects of Effective Stress Paths **293**
- 8.4 Elements of the Critical State Model **294**
  - 8.4.1 Yield Surface **294**
  - 8.4.2 Critical State Parameters **294**
    - 8.4.2.1 Failure Line in ( $p'$ ,  $q$ ) Space **294**
    - 8.4.2.2 Failure Line in ( $e$ ,  $p'$ ) Space **295**
- 8.5 Failure Stresses from the Critical State Model **298**
  - 8.5.1 Drained Triaxial Test **298**
  - 8.5.2 Undrained Triaxial Test **300**
- 8.6 Practical Implications **307**
- 8.7 Soil Stiffness **309**
- 8.8 Strains from the Critical State Model **312**
  - 8.8.1 Volumetric Strains **312**
  - 8.8.2 Shear Strains **314**
- 8.9 Calculated Stress–Strain Response **318**
  - 8.9.1 Drained Compression Tests **319**
  - 8.9.2 Undrained Compression Tests **320**
- 8.10  $K_o$ -Consolidated Soil Response **326**
- 8.11 Relationships Between Simple Soil Tests, Critical State Parameters, and Soil Strengths **329**
  - 8.11.1 Undrained Shear Strength of Clays at the Liquid and Plastic Limits **329**

- 8.11.2 Vertical Effective Stresses at the Liquid and Plastic Limits **329**
- 8.11.3 Undrained Shear Strength–Vertical Effective Stress Relationship **330**
- 8.11.4 Compressibility Indices ( $\lambda$  and  $C_c$ ) and Plasticity Index **330**
- 8.11.5 Undrained Shear Strength, Liquidity Index, and Sensitivity **330**

- 8.12 Summary **331**  
Practical Examples **332**  
Exercises **337**

## **CHAPTER 9** *BEARING OF CAPACITY OF SOILS AND SETTLEMENT OF SHALLOW FOUNDATIONS* **340**

- 9.0 Introduction **340**
- 9.1 Definitions of Key Terms **341**
- 9.2 Questions to Guide Your Reading **342**
- 9.3 Basic Concepts **343**
  - 9.3.1 Collapse and Failure Loads **343**
  - 9.3.2 Failure Surface **343**
- 9.4 Collapse Load Using the Limit Equilibrium Method **345**
- 9.5 Bearing Capacity Equations **347**
- 9.6 Mat Foundations **359**
- 9.7 Bearing Capacity of Layered Soils **361**
- 9.8 Building Codes Bearing Capacity Values **363**
- 9.9 Settlement **364**
- 9.10 Settlement Calculations **366**
  - 9.10.1 Immediate Settlement **366**
  - 9.10.2 Primary Consolidation Settlement **370**
- 9.11 Determination of Bearing Capacity and Settlement of Coarse-Grained Soils from Field Tests **373**
  - 9.11.1 Standard Penetration Test (SPT) **373**
  - 9.11.2 Cone Penetration Test (CPT) **376**
  - 9.11.3 Plate Load Test (PLT) **379**
- 9.12 Horizontal Elastic Displacement and Rotation **381**
- 9.13 Summary **382**  
Practical Examples **382**  
Exercises **396**

## **CHAPTER 10** *PILE FOUNDATIONS* **399**

- 10.0 Introduction **399**
- 10.1 Definitions of Key Terms **400**
- 10.2 Questions to Guide Your Reading **401**
- 10.3 Types of Piles and Installations **401**
  - 10.3.1 Concrete Piles **402**
  - 10.3.2 Steel Piles **402**

10.3.3	Timber Piles	402			
10.3.4	Pile Installation	402			
10.4	Load Capacity of Single Piles	405			
10.5	Pile Load Test	408			
10.6	Methods Using Statics	410			
10.6.1	$\alpha$ -Method	411			
10.6.2	$\beta$ -Method	413			
10.7	Pile Load Capacity Based on SPT and CPT Results	421			
10.8	Pile Groups	426			
10.9	Elastic Settlement of Piles	431			
10.10	Consolidation Settlement Under a Pile Group	434			
10.11	Procedure to Estimate Settlement of Single and Group Piles	435			
10.12	Settlement of Drilled Shafts	439			
10.13	Piles Subjected to Negative Skin Friction	439			
10.14	Pile-Driving Formulas and Wave Equation	442			
10.15	Laterally Loaded Piles	444			
10.16	Summary	449			
	Practical Examples	449			
	Exercises	455			
<b>CHAPTER 11 TWO-DIMENSIONAL FLOW OF WATER THROUGH SOILS 459</b>					
11.0	Introduction	459			
11.1	Definitions of Key Terms	459			
11.2	Questions to Guide Your Reading	460			
11.3	Two-Dimensional Flow of Water Through Porous Media	461			
11.4	Flownet Sketching	463			
11.4.1	Criteria for Sketching Flownets	463			
11.4.2	Flownet for Isotropic Soils	464			
11.4.3	Anisotropic Soil	465			
11.5	Interpretation of Flownet	466			
11.5.1	Flow Rate	466			
11.5.2	Hydraulic Gradient	467			
11.5.3	Static Liquefaction, Heaving, Boiling, and Piping	467			
11.5.4	Critical Hydraulic Gradient	467			
11.5.5	Porewater Pressure Distribution	468			
11.5.6	Uplift Forces	468			
11.6	Finite Difference Solution for Two-Dimensional Flow	473			
11.7	Flow Through Earth Dams	480			
11.8	Soil Filtration	483			
11.9	Summary	484			
	Practical Example	484			
	Exercises	486			
<b>CHAPTER 12 STABILITY OF EARTH RETAINING STRUCTURES 489</b>					
12.0	Introduction	489			
12.1	Definitions of Key Terms	489			
12.2	Questions to Guide Your Reading	490			
12.3	Basic Concepts on Lateral Earth Pressures	491			
12.4	Coulomb's Earth Pressure Theory	498			
12.5	Rankine's Lateral Earth Pressure for a Sloping Backfill and a Sloping Wall Face	502			
12.6	Lateral Earth Pressures for a Total Stress Analysis	503			
12.7	Application of Lateral Earth Pressures to Retaining Walls	506			
12.8	Types of Retaining Walls and Modes of Failure	508			
12.9	Stability of Rigid Retaining Walls	511			
12.9.1	Translation	511			
12.9.2	Rotation	512			
12.9.3	Bearing Capacity	513			
12.9.4	Deep-Seated Failure	513			
12.9.5	Seepage	513			
12.9.6	Procedures to Analyze Gravity Retaining Walls	513			
12.10	Stability of Flexible Retaining Walls	521			
12.10.1	Analysis of Sheet Pile Walls in Uniform Soils	521			
12.10.2	Analysis of Sheet Pile Walls in Mixed Soils	523			
12.10.3	Consideration of Tension Cracks in Fine-Grained Soils	524			
12.10.4	Methods of Analyses	524			
12.10.5	Analysis of Cantilever Sheet Pile Walls	526			
12.10.6	Anchored Sheet Pile Walls	527			
12.11	Braced Excavation	537			
12.12	Mechanical Stabilized Earth Walls	541			
12.12.1	Basic Concepts	543			
12.12.2	Stability of Mechanical Stabilized Earth Walls	543			
12.13	Other Types of Retaining Walls	550			
12.13.1	Modular Gravity Walls	551			
12.13.2	In Situ Reinforced Walls	551			
12.13.3	Chemically Stabilized Earth Walls (CSE)	552			
12.14	Summary	552			
	Practical Examples	552			
	Exercises	558			
<b>CHAPTER 13 SLOPE STABILITY 565</b>					
13.0	Introduction	565			
13.1	Definitions of Key Terms	565			

13.2	Questions to Guide Your Reading	<b>566</b>
13.3	Some Types of Slope Failure	<b>566</b>
13.4	Some Causes of Slope Failure	<b>568</b>
13.4.1	Erosion	<b>568</b>
13.4.2	Rainfall	<b>568</b>
13.4.3	Earthquakes	<b>568</b>
13.4.4	Geological Features	<b>568</b>
13.4.5	External Loading	<b>568</b>
13.4.6	Construction Activities	<b>568</b>
13.4.6.1	Excavated Slopes	<b>570</b>
13.4.6.2	Fill Slopes	<b>570</b>
13.4.7	Rapid Drawdown	<b>570</b>
13.5	Infinite Slopes	<b>571</b>
13.6	Two-Dimensional Slope Stability Analyses	<b>575</b>
13.7	Rotational Slope Failures	<b>575</b>
13.8	Method of Slices	<b>578</b>
13.8.1	Bishop's Method	<b>578</b>
13.8.2	Janbu's Method	<b>580</b>
13.9	Application of the Method of Slices	<b>581</b>
13.10	Procedure for the Method of Slices	<b>583</b>
13.11	Stability of Slopes with Simple Geometry	<b>592</b>
13.11.1	Taylor's Method	<b>592</b>

13.11.2	Bishop–Morgenstern Method	<b>593</b>
13.12	Factor of Safety (FS)	<b>594</b>
13.13	Summary	<b>595</b>
	Practical Example	<b>595</b>
	Exercises	<b>600</b>

**APPENDIX A** *A COLLECTION OF FREQUENTLY USED SOIL PARAMETERS AND CORRELATIONS* **604**

**APPENDIX B** *DISTRIBUTION OF VERTICAL STRESS AND ELASTIC DISPLACEMENT UNDER A UNIFORM CIRCULAR LOAD* **607**

**APPENDIX C** *DISTRIBUTION OF SURFACE STRESSES WITHIN FINITE SOIL LAYERS* **608**

**APPENDIX D** *LATERAL EARTH PRESSURE COEFFICIENTS (KERISEL AND ABSI, 1970)* **611**

*ANSWERS TO SELECTED PROBLEMS* **615**

*REFERENCES* **621**

*INDEX* **626**