Soil Mechanics

Principles and Practice

G. E. Barnes

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Preface

The main aims of this book are to provide an understanding of the nature of soil, an appreciation of soil behaviour and a concise and clear presentation of the basic principles of soil mechanics.

The subject of soil mechanics attempts to provide a framework for understanding the behaviour of the ground by considering the principles which apply to soils. The geotechnical engineer must then use judgement to determine how to apply these principles in real situations.

It is often said that soil mechanics is a 'black art' because these principles may not apply universally, and there is a considerable amount of empirical knowledge which has been built up over the years but which still serves the engineer well. This is also probably a result of trying to apply a purely scientific approach to a material which has not been controlled during its manufacture by human interference. Instead the ground is a natural material, variable, unique, not fully understood and sometimes surprising in its behaviour.

The book is intended as a main text for undergraduate civil and ground engineering students to provide the basic principles and to illustrate how, why and with what limitations these principles can be applied in practice. It is also intended to be retained by these students when they become practitioners and for professionals already in practice as a reference source providing guidance and information for the solution of real geotechnical problems.

It is assumed that the reader will have a basic understanding of mathematics and science and a good understanding of applied mechanics. In civil engineering undergraduate degree courses there is often insufficient emphasis on the need to provide a sound knowledge of geology and, in particular, the superficial geology, in other words, the soils! This material too often gets in the way for many geologists who are mainly interested in the rocks.

A good geotechnical engineer will have a knowledge of mathematics, science and be proficient with soil mechanics but a knowledge of geology, soil profiles and groundwater conditions is fundamental to the application of soil mechanics. For this reason the book aims to consider soil mechanics with more emphasis on its application in the ground and less emphasis on the behaviour of soils in the unnatural environment of the laboratory.

The book contains a range of worked examples to assist the learning of the subject and illustrate the applications of the various analytical approaches. To consolidate this understanding, problem exercises have been included for students to attempt themselves.

I am most grateful to all those researchers, writers and practising engineers who have investigated the subject and collected information over the last seventy years or so, without whom no standard text-book could be written. In particular, I wish to record my thanks to those publishers, organisations and individuals who have granted permission to use material from their publications.

I wish to express my gratitude to Dr Bob Saxton from Plymouth University for reviewing the draft manuscript and making valuable comments. I wish to thank Professor Clive Melbourne, Head of School of Civil Engineering at Bolton Institute for his support and encouragement. Thanks are also due to Miss Joanne Carney for typing the draft manuscript. Finally, my sincere thanks go to my wife, Linda, for her support and understanding during the preparation of the book.

Graham Barnes

List of symbols

A	Activity	D_r	Relative density
A	Area	E'	Young's modulus in terms of effective stress (drained condition)
A'	Effective area	E_p	Pressuremeter modulus
A	Pore pressure parameter	E_u	Young's modulus in terms of total stress (undrained condition)
A_c	Ash content	E	Lateral force on side of slice
A_b	Pile base area	ESP	Effective stress path
A_f	Pore pressure parameter at failure	e	Eccentricity
A_r	Area ratio	e	Void ratio
A_s	Pile shaft area	e_0	Initial void ratio
A_v	Air voids content	e_f	Final void ratio
a	Slope stability coefficient	e_{max}	Void ratio at loosest state
B	% of particles passing maximum size	e_{min}	Void ratio at densest state
B	Width of foundation	F	Factor of safety, length factor
B	Pore pressure parameter	F	Force
$\bar{B}$	Pore pressure parameter	F_d	Enlargement factor
B'	Effective width	F_B	Correction for roughness
b	Slope stability coefficient	F_D	Correction for depth of embedment
C_N	Correction for overburden pressure	f	Shape factor or intake factor
C_w	Correction for water table	f_0	Slope stability correction factor
C_c	Compression index	f_s	Skin friction, sleeve friction
C_c	Coefficient of curvature	f_s	Shape factor
C_α	Coefficient of secondary compression	f_t	Correction for time
C_s	Soil skeleton compressibility	f_t	Permissible tensile strength of reinforcement
C_s	Swelling index	f_y	Yield factor
C_w	Compressibility of pore water	f_l	Thickness factor
CD	Consolidated drained	G	Shear modulus
CU	Consolidated undrained	G_s	Specific gravity of particles
CI	Consistency index	g	Gravitational acceleration (9.81 m/s ²)
CSL	Critical state line	g	Soil constant for the Hvorslev surface
c_a	Adhesion	H	Height, thickness, horizontal force
c_b	Adhesion at underside of foundation	H_c	Constant head above the water table
c_r	Remoulded undrained cohesion	H_0	Initial head above the water table
c_u	Undrained cohesion	H_t	Head at time t
c_v	Coefficient of consolidation, vertical direction	h	Head difference
c_H	Coefficient of consolidation, horizontal direction	h_c	Capillary rise
c_w	Adhesion between soil and wall	h_m	Mean head
c'	Cohesion in effective stress terms	h_p	Pressure head
D	Depth of foundation	h_s	Fully saturated capillary zone
D	Depth factor of slip circle	h_w	Depth to water table
d	Diameter, depth of penetration, particle size	h_z	Elevation or position head
d	Length of drainage path	I	Influence value or factor
d_0	Initial depth of embedment		

<i>ICL</i>	Isotropic normal consolidation line	<i>OCR</i>	Overconsolidation ratio
<i>I_c</i>	Compressibility index	<i>PL</i>	Plastic limit
<i>I_p</i>	Plasticity index (or <i>PI</i>)	<i>PI</i>	Plasticity index (or <i>I_p</i>)
<i>I_z</i>	Strain influence factor	<i>P</i>	Force
<i>i</i>	Hydraulic gradient	<i>P_a</i>	Resultant active thrust or force
<i>i_c</i>	Critical hydraulic gradient	<i>P_p</i>	Resultant passive thrust or force
<i>i_e</i>	Exit hydraulic gradient	<i>P_{an}</i>	Normal component of active thrust
<i>i_m</i>	Mean hydraulic gradient	<i>P_{pn}</i>	Normal component of passive thrust
<i>J</i>	Seepage force	<i>P_w</i>	Horizontal water thrust
<i>K</i>	Absolute or specific permeability	<i>p</i>	Pressure, contact pressure
<i>K₀</i>	Coefficient of earth pressure at rest	<i>p</i>	Stress path parameter (Total stress)
<i>K_{0CL}</i>	<i>K₀</i> normal consolidation line	<i>p'</i>	Stress path parameter (Effective stress)
<i>K_a</i>	Coefficient of active earth pressure	<i>p_c'</i>	Preconsolidation pressure
<i>K_{ac}</i>	Earth pressure coefficient	<i>p_c'</i>	Initial isotropic stress
<i>K_p</i>	Coefficient of passive pressure	<i>p₀'</i>	Present overburden pressure (Effective stress)
<i>K_{pc}</i>	Earth pressure coefficient	<i>p₀</i>	Total overburden pressure
<i>K_s</i>	Coefficient of horizontal pressure	<i>Q</i>	Steady state quantity of flow
<i>k</i>	Coefficient of permeability	<i>Q_{ult}</i>	Ultimate load
<i>k</i>	Coefficient for modulus increasing with depth	<i>Q_s</i>	Ultimate shaft load
<i>L, l</i>	Length, lever arm	<i>Q_b</i>	Ultimate base load
<i>L'</i>	Effective length	<i>Q</i>	Line load surcharge
<i>LL</i>	Liquid limit	<i>q</i>	Flow rate
<i>LI</i>	Liquidity index	<i>q</i>	Uniform surcharge
<i>M</i>	Moment	<i>q</i>	Stress path parameter (Total stress)
<i>M</i>	Gradient of the critical state line on <i>p'</i> - <i>q'</i> plot	<i>q'</i>	Stress path parameter (Effective stress)
<i>MCV</i>	Moisture condition value	<i>q_a</i>	Allowable bearing pressure
<i>m</i>	Mass	<i>q_{app}</i>	Applied pressure (or <i>q</i>)
<i>m</i>	Slope stability coefficient	<i>q_b</i>	End bearing resistance
<i>m_v</i>	Coefficient of volume compressibility	<i>q_c</i>	Cone penetration resistance
<i>N</i>	Normal total force	<i>q_{max}</i>	Maximum bearing pressure
<i>N</i>	Stability number	<i>q_s</i>	Safe bearing capacity
<i>N</i>	Specific volume at <i>p'</i> = 1.0 kN/m ² on <i>ICL</i>	<i>q_{ult}</i>	Ultimate bearing capacity
<i>N</i>	Standard penetration test result, No. of blows	<i>R</i>	Resultant force, distance
<i>N'</i>	Corrected SPT value	<i>R</i>	Dial gauge reading
<i>N'</i>	Normal effective force	<i>R</i>	Radius of influence of drain
<i>N_c</i>	Bearing capacity factor	<i>R_f</i>	Friction ratio
<i>N_q</i>	Bearing capacity factor	<i>R_s</i>	Pile group settlement ratio
<i>N_γ</i>	Bearing capacity factor	<i>R_{3, R_t}</i>	Time correction factors
<i>NC</i>	Normally consolidated	<i>R_T</i>	Correction for temperature
<i>N₀</i>	Specific volume at <i>p'</i> = 1.0 kN/m ² on <i>K_{0CL}</i>	<i>r</i>	Radial distance, or radius
<i>N_s</i>	Stability number	<i>r_d</i>	Radius of well or drain
<i>n</i>	Porosity, number of piles	<i>r_u</i>	Pore pressure ratio
<i>n</i>	Slope stability coefficient	<i>S_r</i>	Degree of saturation
<i>n</i>	Ratio <i>R/r_d</i>	<i>SL</i>	Shrinkage limit
<i>n_d</i>	Number of equipotential drops	<i>s</i>	Spacing of drains, spacing of piles, anchors
<i>n_f</i>	Number of flow paths	<i>s</i>	Stress path parameter (Total stress)
<i>O_c</i>	Organic content	<i>s'</i>	Stress path parameter (Effective stress)
<i>OC</i>	Overconsolidated	<i>T</i>	Shear force, surface tension force, torque

T	Tensile force in reinforcement	α	Shaft adhesion factor
TSP	Total stress path	α_F	Settlement interaction factor
T_v	Time factor for one-dimensional consolidation	α_p	Peak adhesion factor
T_R	Time factor for radial consolidation	β	Angle, relative rotation
t	Time	β	Skin friction factor
t	Stress path parameter (Total stress)	χ	Proportion of cross-section occupied by water
t'	Stress path parameter (Effective stress)	δ	Angle of wall friction, base sliding, piles
U	Water force	Δ	delta, change in, increment of
U, U_c	Uniformity coefficient	Δ	Relative deflection
U_c	Combined or overall degree of consolidation	$\delta\rho$	Differential settlement
U_R	Degree of radial consolidation	$\delta\rho_h$	Differential heave
U_v	Degree of one-dimensional consolidation	ε_α	Coefficient of secondary compression
$\overline{U_v}$	Average degree of consolidation	Φ	Potential function
UU	Unconsolidated undrained	ϕ	Friction angle
u	Horizontal displacement	ϕ_i	ϕ before pile installation
u_a	Pore air pressure	ϕ_u	Angle of failure envelope, undrained condition
u_w	Pore water pressure	ϕ_{cv}	ϕ at constant volume
V	Volume	ϕ_μ	Particle-particle friction angle
V_a	Volume of air	ϕ_m	Mobilised friction angle
V_0	Initial volume	ϕ_r	ϕ at residual strength
V_s	Volume of solids	Γ	Specific volume at $p' = 1.0 \text{ kN/m}^2$ on <i>CSL</i>
V_T	Total vertical load	γ	Unit weight
V_v	Volume of voids	γ_b	Bulk unit weight
V_w	Volume of water	γ_d	Dry unit weight
v	Velocity	$\gamma_{\min}$	Dry unit weight in loosest state
v	Specific volume	$\gamma_{\max}$	Dry unit weight in densest state
v_κ	Specific volume on isotropic swelling line at $p' = 1.0 \text{ kN/m}^2$	γ_{sat}	Saturated unit weight
$v_{\kappa 0}$	Specific volume on anisotropic swelling line at $p' = 1.0 \text{ kN/m}^2$	γ_{sub}	Submerged unit weight
v_s	Seepage velocity	γ_w	Unit weight of water
w	Water content or moisture content	η	Efficiency, viscosity of fluid
w_c	Saturation moisture content of particles	κ	Slope of overconsolidation line
w_e	Equivalent moisture content	λ	Slope of normal consolidation line
W	Weight	λ	Pile adhesion coefficient
W_p	Weight of pile	θ	Rotation, inclination of a plane
W_t	Total weight	μ	Interparticle friction
W_w	Weight of water	μ	Vane correction factor
X	Shear force on side of slice	μ	Correction for consolidation settlement
x, y, z	Coordinate axes	μ_1	Influence factor
Z	Dimensionless depth	μ_0	Correction for depth
Z_1	Depth of influence	μ_r	Correction for rigidity
z	Depth	ν	Poisson's ratio
z_a	Height above the water table	ρ	Mass density
z_c	Critical depth	ρ_b	Bulk density
z_c	Depth of tension crack	ρ_d	Dry density
z_0	Depth of negative active earth pressure	ρ_f	Fluid density
α	Angle, angular strain	ρ_s	Particle density
		ρ_w	Density of water

ρ_{all}	Allowable settlement
ρ_i	Immediate settlement
ρ_c	Consolidation settlement
ρ_h	Heave
ρ_s	Secondary settlement
ρ_t	Consolidation settlement at time t
ρ_T	Total settlement
ρ_y	Immediate settlement including yield
σ	Total stress
σ_N	Normal total stress
σ'	Effective stress
σ'_N	Normal effective stress
σ_m	Mean stress
$\sigma_1, \sigma_2, \sigma_3$	Major, intermediate and minor principal total stresses
$\sigma'_1, \sigma'_2, \sigma'_3$	Major, intermediate and minor principal effective stresses
σ_H, σ'_H	Total and effective horizontal stresses
σ_v, σ'_v	Total and effective vertical stresses
τ	Shear stress
τ_y	Yield stress
ω	Tilt, correction for strength of fissured clays
Ψ	Flow function

Notes on units

SI Units

The International System of units (SI) has been used throughout in this book. A complete guide to the system appears in ASTM E-380 published by the American Society for Testing and Materials. The following is a brief summary of the main units.

The base units used in soil mechanics are

<u>Quantity</u>	<u>Unit</u>	<u>Symbol</u>
length	metre	m
mass	kilogram	kg
time	second	s

Other commonly used units are:

for length:

micron (μm)
millimetre (mm)

for mass:

gram (g)
megagram (Mg)
1 Mg = 1000 kg = 1 tonne or 1 metric ton

for time:

minutes (min)
hours, days, weeks, years

Mass, force and weight

Mass represents the quantity of matter in a body and this is independent of the gravitational force. Weight represents the gravitational force acting on a mass.

Unit force (1N) imparts unit acceleration (1 m/s^2) to unit mass (1 kg). Newton's Law gives

$$\text{Weight} = \text{mass} \times \text{gravitational constant}$$

The acceleration due to gravity on the earth's surface (g) is usually taken as 9.81 m/s^2 so on the earth's surface 1 kg mass gives a force of 9.81 N.

The unit of force is the newton (N) with multiples of

$$\begin{aligned}\text{kilonewton (kN)} &= 1000 \text{ N} \\ \text{meganewton (MN)} &= 10^6 \text{ N}\end{aligned}$$

Measuring scales or balances in a laboratory respond to force but give a measurement in grams or kg, in other words, in mass terms.

Stress and pressure

These have units of force per unit area (N/m^2). The SI unit is the pascal (Pa).

$$\begin{aligned}1 \text{ N/m}^2 &= 1 \text{ Pa} \\ 1 \text{ kN/m}^2 &= 1 \text{ kPa} \\ (\text{kilopascal or kilonewton per square metre}) \\ 1 \text{ MN/m}^2 &= 1 \text{ MPa}\end{aligned}$$

Density and unit weight

Density is the amount of mass in a given volume and is best described as mass density (ρ). The SI unit is kilogram per cubic metre (kg/m^3). Other units are megagram per cubic metre (Mg/m^3).

Density is commonly used in soil mechanics because laboratory balances give a measure of mass.

Unit weight (γ) is the force within a unit volume where

$$\gamma = \rho g$$

The common unit for unit weight is kilonewton per cubic metre (kN/m^3) or sometimes MN/m^3 .

Unit weight is a useful term in soil mechanics since it gives vertical stress directly when multiplied by the depth.

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