

Introduction to SOIL MECHANICS



Béla Bodó & Colin Jones

WILEY Blackwell



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- Supplementary problems
- Solutions to supplementary problems



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Contents

Preface	xii
Dedication and Acknowledgments	xiii
List of Symbols	xiv
1 Soil Structure	1
1.1 Volume relationships	1
1.1.1 Voids ratio (e)	2
1.1.2 Porosity (n)	3
1.1.3 Degree of saturation (S_r)	3
1.2 Weight–volume relationships	6
1.2.1 Bulk densities	7
1.2.2 Dry densities	8
1.2.3 Saturated densities	8
1.2.4 Submerged densities (γ')	9
1.2.5 Density of solids (γ_s)	10
1.2.6 Specific gravity (G_s)	10
1.2.7 Moisture content (m)	11
1.2.8 Partially saturated soil	12
1.2.9 Relative density (D_r)	18
1.3 Alteration of soil structure by compaction	20
1.3.1 Laboratory compaction tests	21
1.3.2 Practical considerations	26
1.3.3 Relative compaction (C_r)	27
1.3.4 Compactive effort	27
1.3.5 Under- and overcompaction	28
1.3.6 Site tests of compaction	28
1.4 California bearing ratio (CBR) test	30
1.5 The pycnometer	35
Supplementary problems for Chapter 1	39
2 Classification of Cohesive Soils	43
2.1 Atterberg Limits	43
2.1.1 Liquid Limit (LL)	43
2.1.2 Plastic Limit	48
2.1.3 Shrinkage Limit	50
2.1.4 Swelling of cohesive soils	56
2.1.5 Saturation Limit ($Z\%$)	56
2.1.6 Relationship between the limits	57
2.1.7 Linear shrinkage and swelling	59
2.2 Consistency indices	64
2.2.1 Plasticity index (PI)	64

2.2.2	Relative consistency index (RI)	64
2.2.3	Liquidity index (LI)	64
2.3	Classification of soils by particle size	69
2.3.1	Sieve analysis	69
2.3.2	Uniformity coefficient (U)	73
2.3.3	Filter design	74
2.3.4	Typical problems	77
2.3.5	Combination of materials	78
2.3.6	Sedimentation tests	85
	Supplementary problems for Chapter 2	91
3	Permeability and Seepage	92
3.1	Coefficient of permeability (k)	93
3.2	Seepage velocity (v_s)	94
3.3	Determination of the value of k	96
3.3.1	Constant head test	96
3.3.2	Falling head test	98
3.4	Field pumping tests	102
3.4.1	Unconfined layer	102
3.4.2	Radius of influence (R)	104
3.4.3	Confined layer under artesian pressure (σ_A)	106
3.5	Permeability of stratified soil	107
3.6	Flow nets	108
3.6.1	Flow lines (FL)	109
3.6.2	Head loss in a flow channel	111
3.6.3	Equipotential lines (EPL)	111
3.6.4	Flow net construction	113
3.6.5	Application of flow nets	114
3.6.6	Seepage flowrate (Q)	114
3.6.7	Seepage pressure	115
3.6.8	Seepage force (S)	119
3.7	Erosion due to seepage	121
3.8	Prevention of piping	128
3.9	Flow net for earth dams	129
	Supplementary problems for Chapter 3	135
4	Pressure at Depth Due to Surface Loading	139
4.1	Concentrated point load	140
4.2	Concentrated line load	142
4.3	Uniform strip loading (Michell's solution)	144
4.4	Bulb of pressure diagrams	147
4.5	Vertical pressure under triangular strip load	151
4.6	Vertical pressure under circular area	156
4.7	Rectangular footing	159
4.8	Footings of irregular shape	163
4.9	Pressure distribution under footings	167
4.9.1	Influence of footing	167
4.9.2	Influence of loading	170
4.10	Linear dispersion of pressure	170
	Supplementary problems for Chapter 4	173

5	Effective Pressure (σ')	175
5.1	Unloaded state	175
5.2	Loaded state	177
5.3	Flooded state	180
5.4	Types of problem	182
5.5	Effect of seepage on shallow footings	194
5.6	Ground water lowering (at atmospheric pressure)	195
5.7	Reduction of artesian pressure	196
5.8	Capillary movement of water	199
5.8.1	Equilibrium moisture content (m_e)	204
5.8.2	Soil suction (S_s)	208
	Supplementary problems for Chapter 5	214
6	Shear Strength of Soils	219
6.1	Coulomb-Mohr Theory	220
6.1.1	Stresses on the plane of failure	221
6.1.2	Friction and cohesion	223
6.1.3	Apparent cohesion	224
6.2	Stress path	224
6.2.1	Stress path failure envelope	225
6.2.2	Variation of stress path	231
6.3	Effect of saturation	234
6.3.1	Effective Mohr's circle	234
6.3.2	Effective stress path (ESP)	234
6.4	Measurement of shear strength	238
6.4.1	Triaxial tests	238
6.4.2	Variation of pore pressure	240
6.4.3	Total excess pore pressure	241
6.4.4	Unconsolidated-undrained tests	242
6.4.5	Quick-undrained test	248
6.4.6	Consolidated-undrained (CU) test	250
6.4.7	Consolidated-drained (CD) test	252
6.4.8	Unconfined compression strength of clays	253
6.4.9	Standard shear box test	256
6.4.10	The Vane shear test	259
6.4.11	Residual shear strength	261
6.5	Thixotropy of clay	263
6.6	Undrained cohesion and overburden pressure	263
	Supplementary problems for Chapter 6	265
7	Consolidation and Settlement	268
7.1	Consolidation	268
7.2	The pressure-voids ratio curve	270
7.2.1	Analytical solution	270
7.2.2	Equation of the σ' - e curve	271
7.2.3	Alternative conventional procedure	274
7.2.4	Graphical solution	276
7.3	Forms of the σ' - e curve	279
7.3.1	Normally consolidated clay	280

7.3.2	Overconsolidated clays	280
7.4	Coefficient of compressibility (a_v)	281
7.5	Coefficient of volume change (m_v)	282
7.5.1	Voids ratio method	282
7.5.2	Direct method	282
7.6	Estimation of settlement	284
7.6.1	Voids ratio method	286
7.6.2	Method using m_v	288
7.6.3	Direct method	289
7.7	Rate of consolidation	291
7.7.1	Variation of excess pore pressure with time	292
7.7.2	Typical pore pressure distributions	293
7.7.3	Estimation of time	294
7.7.4	Coefficient of consolidation (c_v)	295
7.8	Pore pressure isochrones	301
7.8.1	Average percentage consolidation	302
7.9	Coefficient of permeability (k)	310
7.10	Time from similarity	310
7.11	Total settlement	311
7.11.1	Initial compression	311
7.11.2	Primary consolidation	311
7.11.3	Secondary consolidation	312
	Supplementary problems for Chapter 7	314
8	Lateral Earth Pressure	319
8.1	Resistance to active expansion	320
8.2	The value of K_0	321
8.3	Stress path representation	322
8.4	Rankine's theory of cohesionless soil	324
8.4.1	Stress path representation (Lambe)	330
8.5	Rankine-Bell theory for $c-\phi$ soil	334
8.5.1	Tension cracks	335
8.5.2	Effect of surcharge (q kN/m) on z_0	336
8.5.3	Water in the cracks only	336
8.6	Rankine-Bell theory for c -soil	336
8.7	Pressure-force and its line of action	336
8.7.1	Triangular diagram for uniform soil	337
8.7.2	Triangular diagram for water	337
8.7.3	Rectangular diagram for surcharge only	338
8.8	Wall supporting sloping surface	342
8.9	General formulae for $c-\phi$ soil	342
8.9.1	Active case	343
8.9.2	Passive case (with surcharge)	345
8.10	Formulae for pure clay ($\phi = 0$)	349
8.11	Height of unsupported clay	350
8.12	Wedge theories	350
8.12.1	Procedure for cohesionless soil	351

8.12.2	Procedure for cohesive soil	355
8.12.3	Point of application of $P_a(x)$	359
8.12.4	Effect of static water table	360
8.13	Stability of retaining walls	360
8.13.1	Gravity walls	360
8.13.2	Cantilever walls	361
8.13.3	Buttress and counterfort walls	361
8.13.4	Stability check	362
8.14	Sheet piles	368
8.14.1	Cantilever sheet pile walls	369
8.14.2	Factor of safety	370
8.14.3	Bending of sheet piles	374
8.14.4	Sheet pile in cohesive soils	375
8.15	Anchored sheet pile walls	375
8.15.1	Free-earth support method	376
8.15.2	Fixed-earth support method	384
8.15.3	Anchorage	390
8.15.4	Length of tie rod (L)	390
8.15.5	Stability of anchors	390
8.16	Effect of ground water	393
8.17	Stability of deep trenches	400
8.17.1	Horizontal bracing	400
8.18	Bentonite slurry support	406
8.18.1	Trench in clay	407
8.18.2	Trench in sand	408
	Supplementary problems for Chapter 8	413
9	Bearing Capacity of Soils	420
9.1	Terminology	420
9.1.1	Foundation pressure (σ)	420
9.1.2	Net foundation pressure (σ_n)	421
9.1.3	Effective overburden pressure (σ'_0)	421
9.1.4	Ultimate bearing capacity (q_u)	421
9.1.5	Net ultimate bearing capacity (q_n)	421
9.1.6	Safe net bearing capacity (q_{sn})	422
9.1.7	Safe bearing capacity (q_s)	422
9.1.8	Allowable foundation pressure (σ_a)	422
9.1.9	Presumed bearing values	424
9.2	Shallow strip footing	424
9.2.1	Terzaghi's equation for q_u	425
9.2.2	Effect of static water table	428
9.3	Influence of footing shape	435
9.4	Shallow rectangular footing	436
9.4.1	Method of Fellenius	438
9.5	Deep foundations	439
9.5.1	Moderately deep foundations	439
9.6	Standard penetration test (SPT)	443

9.7	Pile foundations $\left(\frac{z}{B} > 5\right)$	445
9.7.1	Types of pile	446
9.8	Some reasons for choosing piles	449
9.9	Some reasons for not choosing piles	451
9.10	Effects necessitating caution	451
9.11	Negative skin friction	453
9.12	Stress distribution around piles	455
9.13	Load-carrying capacity of piles	455
9.13.1	Static formulae	456
9.13.2	End-bearing resistance (Q_e)	456
9.13.3	Shaft resistance (Q_s)	457
9.13.4	Ultimate carrying capacity of pile	458
9.13.5	Allowable carrying capacity of piles (Q_a)	458
9.13.6	Negative skin friction (Q_r)	458
9.14	End bearing resistance and SPT	464
9.15	Influence of pile section on Q_u	465
9.16	Group of piles	465
9.16.1	Eccentrically loaded pile group	468
9.16.2	Settlement of pile groups	471
9.16.3	Raking piles	472
	Supplementary problems for Chapter 9	474
10	Stability of Slopes	479
10.1	Short-term and long-term stability	479
10.2	Total stress analysis (cohesive soils)	480
10.2.1	Homogeneous, pure clay ($\phi_u = 0$)	480
10.2.2	Increasing the value of F_s	481
10.2.3	Minimum value of F_s	482
10.2.4	Potential slip surface	482
10.2.5	Determination of the factor of safety	483
10.2.6	Homogeneous $c-\phi$ soil (total stress analysis)	497
10.2.7	Stratified slopes	500
10.2.8	Slopes under water	501
10.2.9	Taylor's stability numbers	505
10.3	Effective stress analysis (cohesive soils)	513
10.3.1	Method of slices (radial procedure)	513
10.3.2	Bishop's conventional method	518
10.3.3	Bishop's rigorous iterative method	519
10.4	Stability of infinite slopes	523
	Supplementary problems for Chapter 10	528
11	Eurocode 7	530
11.1	Introduction	530
11.2	Recommended units	530
11.3	Limit states	531
11.4	Design procedures	531
11.5	Verification procedures	532
11.6	Application of partial factors	534

Appendices

Appendix A	Mass and Weight	552
Appendix B	Units, Conversion Factors and Unity Brackets	556
Appendix C	Simpson's Rule	562
Appendix D	Resultant Force and Its Eccentricity	567
Appendix E	References	570
Index		572

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Preface

This book is intended to introduce the subject to students studying for BTEC Higher National Certificate/Diploma in Civil Engineering and Building Studies or for a Degree in Civil Engineering. It should also be practical reference to Architects, Geologists, Structural and Geotechnical Technicians.

The primary aim is to provide a clear understanding of the basic concepts of Soil Mechanics. We endeavoured to avoid the temptation of over-elaboration by providing excessively detailed text, unnecessary at this early stage of technical studies.

The purpose of this publication is threefold:

1. To introduce the student to the basics of soil mechanics.
2. To facilitate further advanced study.
3. To provide reference information.

In order to satisfy the above requirements, the concepts of the subject are defined concisely, aided by diagrams, charts, graphs, tables and worked examples as necessary.

The text may appear to be excessively analytical at first sight, but all formulas are derived in terms of basic mathematics, except for a few requiring complicated theory, for those interested in working from first principles. They can be applied however, without reference to the derivation. The expressions are numbered and referred to throughout the text.

There are numerous worked examples on each topic as well as supplementary problems. All examples and problems are solved, many of them interrelated so that solutions can be compared and verified by means of several methods.

Some soil testing procedures are outlined only, as there are a number of excellent, detailed, specialized books and laboratory manuals available to cover this part of the subject.

There is some emphasis on the units employed and on the difference between mass and weight. This subject is discussed in Appendix A.

Béla Bodó and Colin Jones

Dedication

"I dedicate this book to my late wife Dorie."

Béla Bodó

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List of Symbols

Chapter 1

CBR	California bearing ratio
C_r	Relative compaction
D_r	Relative Density
e	Voids ratio
G_s	Specific gravity
k	CBR Load-ring factor
M	Total Mass of sample
m	Moisture (water) content
m_o	Optimum moisture content
M_s	Mass of solids
M_w	Mass of water
n	Porosity
P	CBR applied force
P_a	Percentage of air voids
Q	CBR Load gauge reading
S_r	Degree of saturation
V	Total volume of sample
V_a	Volume of air
V_c	Volume of calibrating cylinder
V_s	Volume of solids
V_v	Volume of voids
V_w	Volume of water
W	Total weight of sample
W_s	Weight of solids
W_w	Weight of water
δ	CBR Penetration distance (delta)
γ	Bulk weight density (Gamma)
γ'	Submerged weight density
γ_d	Dry Weight density
γ_d	Dry Unit weight to be achieved by compaction
γ_s	Weight density of solids
γ_{sat}	Saturated weight density
ρ	Bulk mass density
ρ_d	Dry mass density
ρ_{sat}	Saturated mass density
ρ'	Submerged mass density
ρ_s	Mass density of solids

Chapter 2

C_d	Correction for dispersing agent
C_m	Meniscus correction
D	Equivalent particle diameter
D_{10}	Effective size of a particle
f	Specific Volume change
H	Height from the top of the bulb to surface
h_b	Length of bulb
H_R	Height of centre of bulb to surface
LI	Liquidity index
LL	Liquid limit
M_o	Mass passing the n^{th} sieve
M_r	Mass retained on the n^{th} sieve
m_T	Temperature correction
N	Number of blows
PI	Plasticity index
PL	Plastic limit
P_n	Percentage of soil passing the n^{th} sieve
R	Mixing ratio
R'_h	Recorded hydrometer reading
R_h	Corrected hydrometer reading
RI	Relative consistence index
SL	Shrinkage limit
T	Temperature
t	Time
U	Uniformity coefficient
u	Velocity of sedimentation
V_b	Volume of hydrometer bulb
V_o	Volume of over-dried specimen
\approx	Volume at SL
x	Magnitude of linear shrinkage or swelling
Z	Saturation limit
η	Dynamic viscosity <eta>

Chapter 3

A	Cross-sectional area of specimen
a	Cross-sectional area of standpipe
A_s	Cross-sectional area of solids in specimen
A_v	Cross-sectional area of voids in specimen
EPL	Equipotential line
FL	Flow Line
F_s	Factor of safety
GL	Ground level
GWL	Groundwater level (Water Table)

h	Head loss
H_T	Total head at x
H_x	Head loss to point x
h_x	Pressure head at x
i	Hydraulic gradient
i_{av}	Average hydraulic gradient
i_c	Critical hydraulic gradient
i_e	Exit gradient
k	Coefficient of permeability
L	Length of flow path
N_e	Number of squares (head drops)
N_f	Number of flow channels
N_x	Number of head drops to point x
P	Hydrostatic force
Q	Flowrate
q	Quantity of flow in time (t)
R	Radius of influence
r	Radius to observation well
r_o	Radius of central well
S	Seepage force
u_x	Seepage pore pressure at x
Δh	Head Loss between equipotential line
v	Discharge velocity
v_s	Seepage velocity

Chapter 4

l	Influence factor
n	Number of elements on the Newmark chart
Q	Concentrated point load
q	Uniformly distributed load (UDL)
r	Radius
z	Depth
σ	Horizontal pressure
σ_v	Vertical pressure
τ	Shear stress

Chapter 5

dh	Total deformation of specimen of thickness h
h_A	Artesian pressure head
h_c	Capillary head
h_s	Seepage pressure head
i_c	Critical hydraulic gradient
m_E	Equilibrium moisture content
m_o	Optimum moisture content
pF	Soil suction index
PI	Plasticity index
S_r	Degree of saturation

S_s	Soil suction
T	Surface tension
u	Pore pressure
u_{cs}	Pore pressure in the capillary fringe
u_h	Static pore pressure at depth h
u_s	Seepage pore pressure
z_c	Critical depth for piping
Δu	Small change in u
$\Delta \gamma$	Change in unit weight
$\Delta \sigma$	Small change in σ
$\Delta \sigma'$	Small change in σ'
δ	Deformation of specimen at time t
σ	Total pressure
σ'	Effective pressure
σ_A	Artesian pressure

Chapter 6

A	Pore pressure coefficient
\bar{A}	Pore pressure coefficient
B	Pore pressure coefficient
c	Cohesion
c_u	Undrained shear strength
CD	Consolidated-drained test
CU	Consolidated-undrained test
ESP	Effective stress path
NCC	Normally consolidated clay
n	Proving ring constant
OCC	Over consolidated clay
p & q	Stress path coordinates
p_f & q_f	Stress path coordinates at failure
QU	Quick-undrained test
r_x	Force dial reading at x
TSP	Total stress path
UU	Unconsolidated-undrained test
x	Strain gauge reading
Δu_d	Change in pore pressure due to $\Delta \sigma_d$
Δu_c	Change in pore pressure due to $\Delta \sigma_c$
$\Delta \sigma_c$	Change in cell pressure
$\Delta \sigma_d$	Change in the deviator stress
ε	Strain at x
ϕ	Angle of friction
σ_n	Normal pressure
σ_x	Deviator stress at x
σ_u	Unconfined compression strength
τ	Shear stress
τ_f	Shear stress at failure
τ_p	Shear stress on a plain
τ_m	Maximum shear stress

Chapter 7

A_c	Area indicating completed consolidation
A_t	Area under an isochrone
a_v	Coefficient of compressibility
C_α	Coefficient of Secondary settlement () to consolidation
C_c	Compression index
C_v	Coefficient of consolidation
D_x	Dial reading at stage x
dH_i	Initial settlement
E	Modulus of elasticity
e_0	Initial voids ratio
e_f	Final voids ratio
e_s	Voids ratio after swelling
e_x	Voids ratio at stage x
H	Layer thickness
H_0	Flow path
h_x	Height of specimen at stage x
I_p	Influence factor
k	Coefficient of permeability
m_v	Coefficient of volume change
OCR	Overconsolidation ratio
q	Bearing pressure
T_v	Time factor
t	Time
U	Average degree of consolidation
U_z	Degree of consolidation
u	Pore pressure at time t
u_0	Initial pore pressure
ΔH	Long-term consolidation settlement
$\Delta\sigma'$	Effective consolidating pressure
δ	Depth factor (Delta)
∞	Poisson's ratio (My)
σ'_x	Effective pressure at stage x

Chapter 8

c_u	Unconfined compression strength
c_w	Adhesion between soil and wall
e	Eccentricity
F_ϕ	Factor of safety in terms of friction angle
f_{\max}	Maximum compressive stress
f_{\min}	Minimum compressive stress
F_s	Factor of safety
H	Height of wall
H_0	Height of unsupported clay
K	Coefficient of lateral pressure

K_0	Coefficient of earth pressure at rest
K_a	Coefficient of active earth pressure
K_f	Coefficient of earth pressure at failure
K_p	Coefficient of passive earth pressure
L	Length of slip surface
M_{\max}	Maximum bending moment
M_0	Overturning moment
M_R	Resisting moment
P_a	Active force
P_p	Passive force
P_w	Force of water in tension crack
R	Force on wedge
T	Tension force in tie rod
z_c	Pile penetration
z_0	Depth of tension crack
δ	Angle of wall friction
ϕ'_m	Mobilised friction
μ	Coefficient of friction
σ_a	Active earth pressure
σ_c	Cell pressure in triaxial test
σ_d	Deviator stress in triaxial test
σ_p	Passive earth pressure
σ'_a	Effective active earth pressure
σ'_p	Effective passive earth pressure
$\bar{\sigma}$	Average pressure
τ_f	Shear stress at failure

Chapter 9

\bar{c}_u	Average undrained shear strength
A_e	End bearing area
A_s	Surface area of pile
B	Width of footing
c	Cohesion
F_o	Overall factor of safety
F_s	Factor of safety
K_s	Average coefficient of earth pressure
l	Length of pile
N	Number of SPT blows
n	Number of piles
N'	Corrected value of N
N_c	} Bearing capacity factors
N_q	
N_γ	
P	Failure load on pile
Q	Design working load
Q_a	Allowable carrying capacity of pile
Q_{ag}	Allowable carrying capacity of pile group

Q_e	End bearing resistance
Q_f	Negative skin friction
Q_s	Shaft resistance
Q_u	Ultimate carrying capacity of pile
Q_{ug}	Ultimate carrying capacity of pile group
q_n	Net ultimate bearing capacity
q_s	Safe bearing capacity
q_{sn}	Safe net bearing capacity
q_u	Ultimate bearing capacity
SPT	Standard penetration test
W_p	Weight of pile
α	Adhesion factor (Alpha)
δ	Angle of friction between soil and pile (Delta)
η	Efficiency of pile group (Eta)
ϕ	Angle of friction
σ	Safe bearing pressure of footing
σ_n	Net bearing pressure of footing
$\bar{\sigma}'_o$	Average effective overburden pressure
σ'_o	Effective overburden pressure

Chapter 10

c_u	Shear strength
F	Friction force
F_C	Factor of safety with respect to cohesion
F_S	Factor of safety
F_ϕ	Factor of safety with respect to friction
L	Length of slip surface
M_D	Disturbing moment
M_R	Resisting moment
N	Normal (or radial) component of W
N_C	Stability number
R	Radius of slip circle
r_u	Pore pressure ratio
S	Shear force
T	Tangential component of W
W	Weight

Chapter 11

The comprehensive list of symbols for EC7 is given in *Eurocode 7. Geotechnical design Part 1: General rule*. Only some of the symbols, applied in this book, are reproduced here:

E_d	Design value of the effect of actions
$E_{dst;d}$	Design value of the effect of destabilizing action
$E_{stb;d}$	Design value of the effect of stabilizing action
F_d	Design value of an action
F_{rep}	Representative value of an action
F_s	Factor of safety

$G_{dst;d}$	Design value of destabilising permanent action
$G_{stb;d}$	Design value of stabilising permanent action
$Q_{dst;d}$	Design value of destabilising variable action
R_d	Design value of resistance action
$S_{dst;d}$	Design value of destabilising seepage force
T_d	Design value of total shear resistance
$U_{dst;d}$	Design value of destabilising pore water pressure
$V_{dst;d}$	Design value of destabilising vertical action
X_d	Design value of a material property
X_k	Characteristics value of a material property
γ_G	Partial factor for a permanent action
$\gamma_{G;dist}$	Partial factor for a destabilising action
$\gamma_{G;stb}$	Partial factor for a stabilising action
γ_m	Partial factor for soil parameters (material property)
γ_Q	Partial factor for a variable action
$\gamma_{R;h}$	Partial factor for sliding resistance

Chapter 1

Soil Structure

Soils consist of solid particles, enclosing voids or pores. The voids may be filled with air or water or both. These three soil states (or phases) can be visualized by the enlargement of three small samples of soil.

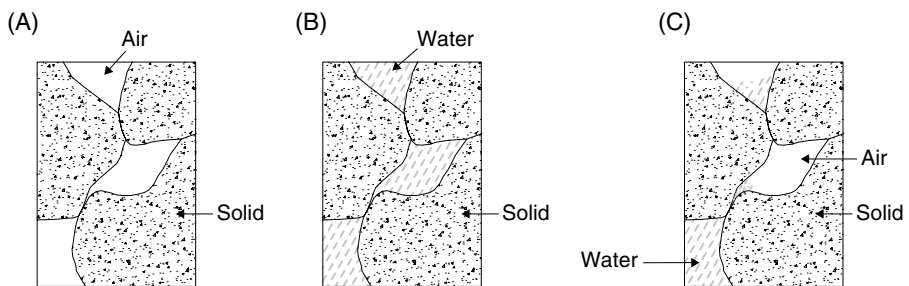


Figure 1.1

Sample A: The soil is oven-dry, that is there is only air in the voids.

Sample B: The soil is saturated, that is the voids are full of water.

Sample C: The soil is partially saturated, that is the voids are partially filled with water.

The above three soil states can be described mathematically by considering:

1. Volume occupied by each constituent.
2. Mass (or weight) of the constituents.

1.1 Volume relationships

The expressions derived in this section will answer two questions:

1. How much voids and solids are contained in the soil sample?
2. How much water is contained in the voids?

In order to obtain these answers, the partially saturated sample (C) is examined. It is assumed, for the purpose of analysis, that the soil particles are lumped together into a homogeneous mass. Similarly, the voids are combined into a single volume, which is

partly occupied by a volume of water. The idealisation of the sample, indicating the volumes occupied by the constituents, is shown diagrammatically in Figure 1.2b.

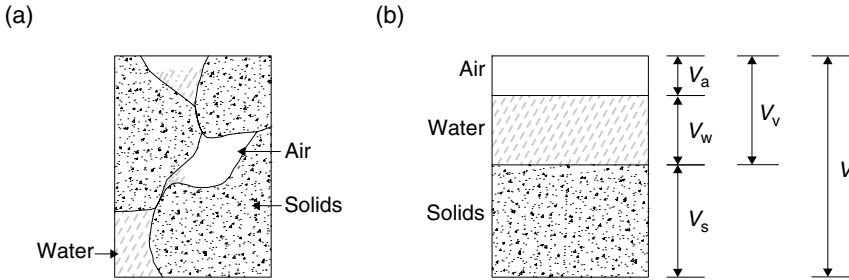


Figure 1.2

Idealized representation of sample C.

- Where: V = Total volume of the sample
- V_v = Volume of voids in the sample
- V_s = Volume of soil in the sample
- V_w = Volume of water in the sample
- V_a = Volume of air in the sample

The basic relationships between the volumes can be seen in the diagram.

Total volume: $V = V_s + V_v$ (1.1)

Volume of voids: $V_v = V_w + V_a$ (1.2)

Hence: $V = V_s + V_w + V_a$ (1.3)

Three important relationships are derived from the basic ones. These are:

- e = voids ratio (or void ratio)
- n = porosity
- S_r = degree of saturation

1.1.1 Voids ratio (e)

This shows the percentage of voids present in the sample, compared to the volume of solids. Thus, if V_s is considered to be 100%, then V_v is $e\%$.

Hence:
$$e = 100 \frac{V_v}{V_s} \% \tag{1.4}$$

For example: if $V_s = 60 \text{ cm}^3$
 and $V_v = 15 \text{ cm}^3$
 then $e = 100 \frac{15}{60} = 25\%$

That is, the volume of voids is 25% of the volume of solids, in this particular sample. Alternatively, the voids ratio may be expressed as a decimal e.g. $e = 0.25$.

Formula (1.4) now becomes:
$$e = \frac{V_v}{V_s} \tag{1.5}$$

The ratio of voids to solids in a sample is represented by Figure 1.3.

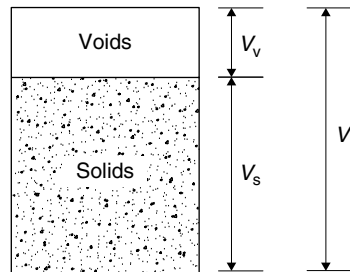


Figure 1.3

1.1.2 Porosity (n)

This shows how many percent of voids are present in the sample, compared to the total volume V . Thus, if V is considered to be 100%, then V_v is $n\%$.

$$n = 100 \frac{V_v}{V} \% \quad (1.6)$$

For example: if $V = 75 \text{ cm}^3$
 and $V_v = 15 \text{ cm}^3$
 then $n = 100 \frac{15}{75} = 20\%$

That is, the volume of voids is 20% of the total volume of the sample of soil.

Again, n maybe expressed as a decimal number $n = 0.2$.

Formula (1.6) now becomes: $n = \frac{V_v}{V} \quad (1.7)$

The diagrammatic representation of porosity is:

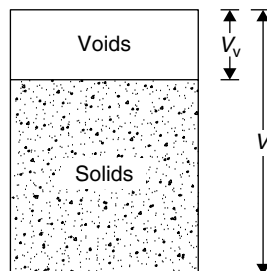


Figure 1.4

1.1.3 Degree of saturation (S_r)

This shows the percentage of voids filled with water. Thus, if V_v is considered to be 100%, then V_w is $S_r\%$.

$$S_r = 100 \frac{V_w}{V_v} \% \quad (1.8)$$

For example, if $V_w = 6 \text{ cm}^3$
 and $V_v = 15 \text{ cm}^3$
 then $S_r = 100 \frac{6}{15} = 40\%$

That is, water fills 40% of the volume of voids. In decimal form $S_r = 0.4$ and formula (1.8) becomes:

$$S_r = \frac{V_w}{V_v} \tag{1.9}$$

Diagrammatically,

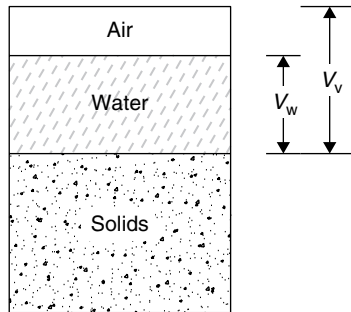


Figure 1.5

Note: For oven-dry soil (Sample A, Figure 1.1):

$$V_w = 0, \text{ hence } S_r = 0$$

For fully saturated soil (Sample B, Figure 1.1):

$$V_w = V_v, \text{ hence } S_r = 1$$

For partially saturated soil therefore: $0 < S_r < 1$

Combined formulae

The quantities defined by formulae (1.1) to (1.9) can be interrelated:

$$\begin{array}{l} \text{From (1.1): } V = V_s + V_v \\ \text{From (1.5): } V_v = eV_s \end{array} \quad \left| \begin{array}{l} \text{either } V = V_s + eV_s \\ \text{or } V = \frac{V_v}{e} + V_v \end{array} \right. \quad \therefore \boxed{V = (1 + e)V_s} \tag{1.10}$$

$$= \left(\frac{1}{e} + 1 \right) V_v \quad \therefore \boxed{V_v = \left(\frac{1 + e}{e} \right) V_v} \tag{1.11}$$

$$\begin{array}{l} \text{From (1.7): } n = \frac{V_v}{V} \\ \text{From (1.10): } V = (1 + e)V_s \end{array} \quad \left| \quad n = \frac{eV_s}{(1 + e)V_s} \quad \therefore \boxed{n = \frac{e}{1 + e}} \tag{1.12}$$

$$\text{From (1.12): } n = \frac{e}{1 + e} \quad \left| \quad \begin{array}{l} n + ne = e \\ n = e(1 - n) \end{array} \quad \boxed{e = \frac{n}{1 - n}} \tag{1.13}$$

$$\begin{array}{l} \text{From (1.9): } S_r = \frac{V_w}{V_v} \\ \text{From (1.11): } V_v = \frac{eV}{1+e} \end{array} \quad \left| \quad S_r = \frac{V_w}{\frac{eV}{1+e}} \quad \therefore \quad S_r = \left(\frac{1+e}{e} \right) \frac{V_w}{V} \right. \quad (1.14)$$

$$\text{From (1.12): } n = \frac{e}{1+e} \quad \text{or} \quad S_r = \frac{V_w}{nV} \quad (1.15)$$

Example 1.1

Given: $V = 946 \text{ cm}^3$ Calculate: V_v , V_a , e , n and S_r

$$V_s = 533 \text{ cm}^3$$

$$V_w = 303 \text{ cm}^3$$

$$\text{From (1.1): } V_v = V - V_s = 946 - 533 = 413 \text{ cm}^3$$

$$\text{From (1.2): } V_a = V_v - V_w = 413 - 303 = 110 \text{ cm}^3$$

$$\text{From (1.5): } e = \frac{V_v}{V_s} = \frac{413}{533} = 0.775, \text{ that is the volume of voids is 77.5\% that of solids.}$$

$$\text{From (1.7): } n = \frac{V_v}{V} = \frac{413}{946} = 0.437$$

$$\text{or From (1.12): } n = \frac{e}{1+e} = \frac{0.775}{1.775} = 0.437$$

That is, the volume of voids is 43.7% of the sample.

$$\text{From (1.9): } S_r = \frac{V_w}{V_v} = \frac{303}{413} = 0.73$$

$$\text{or From (1.15): } S_r = \frac{V_w}{nV} = \frac{303}{(0.437 \times 946)} = 0.73$$

That is, water fills 73% of voids.
The sample is partially saturated.

Example 1.2

A sample of sand was taken from below the ground water table. The volumes measured were:

$$V = 1000 \text{ cm}^3 \quad \text{Calculate: } V_v, V_a, V_s, e \text{ and } n$$

$$V_w = 400 \text{ cm}^3$$

Note: Assume sand samples taken from above the water table as partially saturated ($S_r < 1$) and saturated ($S_r = 1$) if taken from below.

In this example, therefore, $S_r = 1 \quad \therefore \quad V_a = 0$.

$$\text{From (1.8)} \quad S_r = \frac{V_w}{V_v} = 1 \quad \therefore \quad \boxed{V_w = V_v} \quad (1.16)$$

$$V_v = 400 \text{ cm}^3$$

From (1.2): $V_a = V_v - V_w = 400 - 400 = 0$ The voids are full of water

From (1.1): $V_s = V - V_v = 1000 - 400 = 600 \text{ cm}^3$

From (1.5): $e = \frac{V_v}{V_s} = \frac{400}{600} = 0.67$ | V_v is 67% of V_s

From (1.7): $n = \frac{V_v}{V} = \frac{400}{1000} = 0.4$ | V_v is 40% of V

1.2 Weight-volume relations

As the title implies, the formulae derived in this section take into account the weights of V_s and V_w . It is assumed that air is weightless. The weight volume relations are shown diagrammatically:

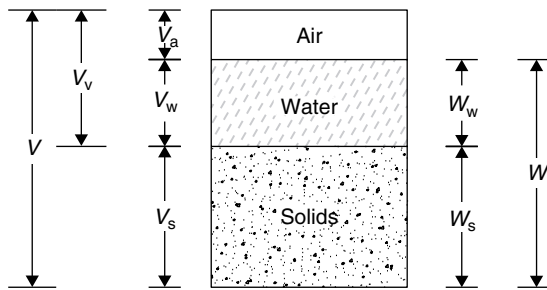


Figure 1.6

Where: W_s = Weight of solids | From Figure 1.6 $W = W_s + W_w$ (1.17)

W_w = Weight of water

W = Total weight

Note: The concepts of mass and weight are defined in Appendix A. Suffice to say here, that if mass (M) is given in kilograms, then weight (W) is calculated from:

$$W = 9.81 \times \text{mass } (M)N \quad \therefore \boxed{W = 9.81 \times 10^{-3} \times M \text{ kN}} \quad (1.18)$$

Several important relationships are derived below in terms of mass, weight and volume. These are:

- ρ = bulk mass density
- γ = bulk weight density (unit weight)
- ρ_d = dry mass density
- γ_d = dry weight density
- ρ_{sat} = saturated mass density
- γ_{sat} = saturated weight density