10TH EDITION

SMITH'S
ELEMENTS OF SOIL MECHANICS

IAN SMITH

WILEY Blackwell

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Preface

When the ninth Edition of this book was published in 2014, I was pleased to receive positive feedback for making the understanding of the new geotechnical design code, Eurocode 7, straightforward and easy to follow. At that same time, a review of all Eurocodes commenced with the intention of producing a 'second generation' of the codes containing improvements and changes to the design procedures. The second generation of the Eurocodes will be published throughout the 2020s and Eurocode 7, in particular, is set to be significantly different from the first generation of the code.

The changes in the new Eurocode 7 affect many aspects of the existing design procedure, and I describe these and explain how to perform the new geotechnical design process in this tenth edition of the book. Many new worked examples help to illustrate the new procedures. Since the first generation of Eurocode 7 is still very much in use in geotechnical design, I have retained the content on it so that readers of this book can gain a thorough understanding of the design procedures used in both generations of the code.

As with the ninth edition, to help the reader fully understand the stages of a Eurocode 7 design, I have arranged the sequence of chapters in the book appropriately: Chapter 6 describes the design methods (aligning mainly to Eurocode 7 Part 1) and Chapter 7 describes the ground investigation aspects (aligning to Part 2). The new Part 3 of the second generation of the code is then introduced in the appropriate later chapters in the book (e.g. retaining structures, shallow and deep foundations).

In recognition of the growing coverage of geomechanical modelling in university degrees, I have introduced a brand-new chapter on constitutive modelling in geomechanics (Chapter 16). The content of this chapter was provided by my friend and colleague Dr Rodaina Aboul Hosn from the *École Spéciale des Travaux Publics*, Paris. What Rodaina does not know about constitutive modelling is not worth knowing, and I owe her an immense amount of thanks for her excellent work. I have embedded Rodaina's work into my style of writing so that the chapter sits neatly alongside all the other chapters.

In addition to the above new content, I have also updated all sections on laboratory and field testing to align the descriptions of the procedures with the new international standards for these tests (Chapters 1, 4 and 7). Another update introduced in this edition is highway pavement foundation design (Chapter 15) – brought about as a result of revisions to the UK Design Manual for Roads and Bridges (DMRB). The early chapters of the book continue to cover the fundamentals of the behaviour of soils. To ease understanding of critical state soil mechanics, I have rearranged and expanded this subject and this is now in a new chapter alongside description of stress paths (Chapter 5).

As with previous editions, I have provided many worked examples throughout the book that illustrate the principles of soil mechanics and the geotechnical design processes. To help the reader further, I have produced a suite of spreadsheets and documents to accompany the book that match up against many of the worked examples. These can be used to better understand the analysis being adopted in the examples. In addition, I have produced the solutions to the exercises at the end of the chapters, a suite of video animations of lab tests and geotechnical processes, and various other teaching resources to accompany the book. All of these files can be freely downloaded from the companion website.

The content of the book aligns to the subjects typically covered in all university geotechnics courses. Teachers should find the content and teaching resources helpful for the own needs, and students will find that the book covers all courses in all years of their degree – all written in an easy-to-follow style.

In addition to Dr Aboul Hosn, I must also express my thanks to Dr Andrew Bond (past Chair TC250/SC7 – Eurocode 7) and to Dr Daniel Barreto (Edinburgh Napier University) for answering the various questions I posed to them as I wrote this edition.

Professor Ian Smith
Edinburgh, January 2021

About the Author

Ian Smith is a freelance Geotechnical and Educational consultant, and Professor of Geotechnical Engineering and Leader of the Built Environment Education at Heriot Watt University, Edinburgh. He has taught Geotechnical Engineering for 25 years at various universities across the globe, having spent some years beforehand working in the site investigation industry. He was Head, then Dean, of the School of Engineering and the Built Environment at Edinburgh Napier University before leaving to set up his own consultancy in 2017. He is an authority on the use of Eurocode 7 in geotechnical design, and has instructed designers and academics in the use of the code throughout the UK, Europe and in China. He is also Visiting Professor at three universities in China and is regularly invited to teach geotechnical engineering at universities across Europe and Asia.

Notation Index

The following is a list of the more important symbols used in the text.

Notation specific to the second generation of Eurocode 7 are indicated where appropriate.

A	Area, pore pressure coefficient
A'	Effective foundation area
A_b	Area of base of pile
A_s	Area of surface of embedded length of pile shaft
B	Width, diameter, pore pressure coefficient, foundation width
B'	Effective foundation width
C	Cohesive force, constant
C_a	Area ratio
C_C	Compression index, soil compressibility, coefficient of curvature
$C_{d,SLS}$	Eurocode 7 serviceability limit state limiting design value
C_N	SPT overburden correction factor
C_r	Static cone resistance
C_s	Constant of compressibility
C_u	Uniformity coefficient
C_v	Void fluid compressibility
C_w	Adhesive force
D	Diameter, depth factor, foundation depth, embedded length of pile
D_w	Depth of groundwater table
D_r	Relative density
D_1, D_2	Cutting shoe diameters
D_{10}, D_{30}, D_{60}	Effective particle sizes (10, 30, 60%)
E	Modulus of elasticity, efficiency of pile group
E'_0	One-dimensional modulus of elasticity
E_d	Eurocode 7 design value of effect of actions
$E_{dst;d}$	Eurocode 7 design value of effect of destabilising actions
$E_{stb;d}$	Eurocode 7 design value of effect of stabilising actions
E_M	Pressuremeter modulus
E_m	Eurocode 7 design value of modulus of elasticity
E_r	SPT energy ratio
F	Factor of safety
F_b	Factor of safety on pile base resistance
$F_{c;d}$	Eurocode 7 design axial compression load on a pile
F_d	Eurocode 7 design value of an action
F_{rep}	Eurocode 7 representative value of an action
F_s	Factor of safety on pile shaft resistance

G; G'	Shear modulus; effective shear modulus
G_k; G_d	Eurocode 7 (2nd G) characteristic permanent action; design permanent action
$G_{dst;d}$	Eurocode 7 design value of destabilising permanent vertical action (uplift)
G_s	Particle specific gravity
$G_{stb;d}$	Eurocode 7 design value of stabilising permanent vertical action (uplift)
$G'_{stb;d}$	Eurocode 7 design value of stabilising permanent vertical action (heave)
G_{wk}	Eurocode 7 (2nd G) characteristic value of G_w
$G_{w,rep}$	Eurocode 7 (2nd G) representative value of G_w
$G_{wk;inf}$	Eurocode 7 (2nd G) inferior (lower) characteristic value of G_w
$G_{wk;sup}$	Eurocode 7 (2nd G) superior (upper) characteristic value of G_w
H	Thickness, height, horizontal load
I	Index, moment of inertia
I_D	Density index
I_L	Liquidity index
I_P	Plasticity index, immediate settlement coefficient
I_σ	Vertical stress influence factor
K	Boussinesq Influence factor, ratio of σ_3/σ_1, bulk/volumetric modulus
K'	Effective bulk/volumetric modulus
K_a	Coefficient of active earth pressure
K_F	Eurocode 7 (2nd G) action consequence factor
K_M	Eurocode 7 (2nd G) material consequence factor
K_0	Coefficient of earth pressure at rest
K_p	Coefficient of passive earth pressure
K'_{ps}	Effective plane strain bulk/volumetric modulus
K_s	Pile constant
L	Length
L'	Effective foundation length
M	Moment, slope projection of critical state line, mass, mobilisation factor
M_s	Mass of solids
M_w	Mass of water
N	Number, stability number, uncorrected blow count in SPT
N_{60}	Number of blows from the SPT corrected to energy losses
$(N_1)_{60}$	Number of blows from the SPT corrected to energy losses, rod length and normalised for effective vertical overburden stress
N_c, N_q, N_γ	Bearing capacity coefficients
N_p	Immediate settlement coefficient
P	Force
P_a	Thrust due to active earth pressure
P_p	Thrust due to passive earth pressure
P_w	Thrust due to water or seepage forces
Q	Total quantity of flow in time t, applied surface line load
Q_b	Ultimate soil strength at pile base
Q_k; Q_d	Eurocode 7 (2nd G) characteristic variable action; design variable action
Q_s	Ultimate soil strength around pile shaft
Q_u	Ultimate load carrying capacity of pile
R	Radius, reaction
$R_{b;cal}$	Eurocode 7 calculated value of pile base resistance
$R_{b;k}$	Eurocode 7 characteristic value of pile base resistance
$R_{b,rep}$	Eurocode 7 (2nd G) representative base resistance

R_c	Eurocode 7 compressive resistance of ground against a pile at ultimate limit state
$R_{c;cal}$	Eurocode 7 calculated value of R_c
$R_{c;d}$	Eurocode 7 design value of R_c
R_{cd}	Eurocode 7 (2nd G) design value of R_c
$R_{c;k}$	Eurocode 7 characteristic value of R_c
$R_{c;m}$	Eurocode 7 measured value of R_c
$R_{c,rep}$	Eurocode 7 (2nd G) representative total pile resistance
R_d	Eurocode 7 design resisting force
R_o	Overconsolidation ratio (one-dimensional)
R_p	Overconsolidation ratio (isotropic)
$R_{s;cal}$	Eurocode 7 calculated value of pile shaft resistance
$R_{s;k}$	Eurocode 7 characteristic value of pile shaft resistance
$R_{s,rep}$	Eurocode 7 (2nd G) representative shaft resistance
S	Vane shear strength
$S_{dst;d}$	Eurocode 7 design value of destabilising seepage force
S_r	Degree of saturation
S_t	Sensitivity
T	Time factor, tangential force, surface tension, vane torque
T_d	Eurocode 7 design value of total shearing resistance around structure
U	Average degree of consolidation
U_z	Degree of consolidation at a point at depth z
V	Volume, vertical load
V_a	Volume of air, percentage air voids
$V_{dst;d}$	Eurocode 7 design value of destabilising vertical action on a structure
V_s	Volume of solids
V_v	Volume of voids
V_w	Volume of water
W	Weight
W_s	Weight of solids
W_w	Weight of water
X_d	Eurocode 7 design value of a material property
X_k	Eurocode 7 representative value of a material property
	Eurocode 7 (2nd G) characteristic value of a material property
X_{rep}	Eurocode 7 (2nd G) representative value of a material property
Z	Section modulus
a	Area, wall adhesion, intercept of MCV calibration line with w-axis
b	Width, slope of MCV calibration line
c	Unit cohesion
c'	Unit cohesion with respect to effective stresses
c_b	Undisturbed soil shear strength at pile base
c'_d	Eurocode 7 design value of effective cohesion
c_r	Residual value of cohesion
c_u	Undrained unit cohesion
$\overline{c_u}$	Average undrained shear strength of soil
$c_{u;d}$	Eurocode 7 design value of undrained shear strength
c_v	Coefficient of consolidation
c_w	Unit cohesion between wall and soil
d	Pile penetration, pile diameter, particle size
d_c, d_q, d_γ	Depth factors

e	Void ratio, eccentricity
f	Settlement coefficient
f_s	Ultimate skin friction for piles
g	Gravitational acceleration
h	Hydraulic head, height, head loss
h_c	Capillary rise, tension crack depth
h_e	Equivalent height of soil
h_w	Excess head
i	Hydraulic gradient
i_c	Critical hydraulic gradient
i_c, i_q, i_γ	Inclination factors
k	Coefficient of permeability
l	Length, length of flow path
m	Stability coefficient
m_B, m_L	Eurocode 7 load inclination factor parameters
m_v	Coefficient of volume compressibility
n	Porosity, stability coefficient
p	Pressure, mean pressure, mean normal stress
p'	Mean normal effective stress
p_a	Active earth pressure
p_c	Preconsolidation pressure (one-dimensional)
p'_e	Equivalent consolidation pressure (isotropic)
p_{LM}	Pressuremeter limit pressure
p_0	Earth pressure at rest
p'_m	Preconsolidation pressure (isotropic)
p'_o	Effective overburden pressure
p_p	Passive earth pressure
q	Unit quantity of flow, deviator stress, uniform surcharge, bearing pressure
q'	Effective deviator stress
q_a	Allowable bearing pressure
q_u	Ultimate bearing capacity
$q_{u\ net}$	Net ultimate bearing capacity
r	Radius, radial distance, finite difference constant
r_u	Pore pressure ratio
s	Suction value of soil, stress parameter, settlement
s_c, s_q, s_γ	Shape factors
s_w	Corrected drawdown in pumping well
t	Time, stress parameter
u, u_w	Pore water pressure
u_a	Pore air pressure, pore pressure due to σ_3 in a saturated soil
u_d	Pore pressure due to $(\sigma_1 - \sigma_3)$ in a saturated soil
$u_{dst;d}$	Eurocode 7 design value of destabilising total pore water pressure
u_i	Initial pore water pressure
u_t	Pore water pressure at toe of sheet pile wall
v	Velocity, specific volume
w	Water, or moisture, content
w_L	Liquid limit
w_P	Plastic limit
w_s	Shrinkage limit

x	Horizontal distance
y	Vertical, or horizontal, distance
z	Vertical distance, depth
z_a	Depth of investigation points
z_o	Depth of tension crack
z_w	Depth below water table
α	Angle, pile adhesion factor, slope of K_f line
β	Slope angle
Γ	Eurocode 7 over-design factor, specific volume at ln p′ = 0
γ	Unit weight (weight density), shear strain
γ'	Submerged, buoyant or effective unit weight (effective weight density)
$\gamma_{A;dst}$	Eurocode 7 partial factor: accidental action – unfavourable
γ_b	Bulk unit weight (bulk weight density), Eurocode 7 partial factor: pile base resistance
$\gamma_{c'}$	Eurocode 7 partial factor: effective cohesion
γ_{cu}	Eurocode 7 partial factor: undrained shear strength
γ_d	Dry unit weight (dry weight density)
γ_E	Eurocode 7 partial factor for effects of actions, Eurocode 7 (2nd G) partial factor for unfavourable effects of actions
$\gamma_{E,fav}$	Eurocode 7 (2nd G) partial factor for favourable effects of actions
γ_F	Eurocode 7 partial factor for an action
γ_G	Eurocode 7 (2nd G) partial factor for permanent unfavourable/destabilising action
$\gamma_{G;dst}$	Eurocode 7 partial factor: permanent action – unfavourable
$\gamma_{G,fav}$	Eurocode 7 (2nd G) partial factor for permanent favourable action
$\gamma_{G;stb}$	Eurocode 7 partial factor: permanent action – favourable
$\gamma_{G,w}$	Eurocode 7 (2nd G) partial factor for unfavourable/destabilising water action
$\gamma_{G,w,stb}$	Eurocode 7 (2nd G) partial factor for stabilising water action
γ_M	Eurocode 7 partial factor for a soil parameter
γ_Q	Eurocode 7 (2nd G) partial factor for variable (unfavourable) action
$\gamma_{Q;dst}$	Eurocode 7 partial factor: variable action – unfavourable
$\gamma_{Q,w}$	Eurocode 7 (2nd G) partial factor for unfavourable water action
γ_{qu}	Eurocode 7 partial factor: unconfined compressive strength
γ_R	Eurocode 7 partial factor for a resistance
γ_{Rb}	Eurocode 7 (2nd G) pile design base resistance factor
γ_{Rc}	Eurocode 7 (2nd G) pile design total resistance factor
γ_{Rd}	Eurocode 7 (2nd G) pile design model factor
γ_{Re}	Eurocode 7 partial factor: earth resistance
γ_{Rh}	Eurocode 7 partial factor: sliding resistance
γ_{Rs}	Eurocode 7 (2nd G) pile design shaft resistance factor
γ_{Rv}	Eurocode 7 partial factor: bearing resistance
γ_s	Eurocode 7 partial factor: pile shaft resistance
γ_{sat}	Saturated unit weight (saturated weight density)
γ_t	Eurocode 7 partial factor: pile total resistance
$\gamma_{\tan\delta}$	Eurocode 7 (2nd G) partial factor: ground/structure interface friction
$\gamma_{\tan\phi}$	Eurocode 7 (2nd G) partial factor: angle of shearing resistance
γ_{ts}	Eurocode 7 (2nd G) partial factor: effective shear strength
γ_w	Unit weight of water (weight density of water)
γ_γ	Eurocode 7 partial factor: weight density
$\gamma_{\phi'}$	Eurocode 7 partial factor: angle of shearing resistance
δ	Ground–structure interface friction angle

ε	Strain
η	Dynamic viscosity of water, conversion factor
θ	Angle of failure plane to major principal plane, angle subtended at centre of slip circle
κ	Slope of swelling line
λ	Slope of normal consolidation line, SPT rod length correction factor
μ	Settlement coefficient, one micron
ν	Poisson's ratio
ξ_m	Eurocode 7 (2nd G) pile design correlation factor
ξ_1, ξ_2	Eurocode 7 correlation factors to evaluate results of static pile load tests
ξ_3, ξ_4	Eurocode 7 correlation factors to derive pile resistance from ground investigation results
ρ	Density, settlement
ρ'	Submerged, buoyant or effective density
ρ_b	Bulk density
ρ_c	Consolidation settlement
ρ_d	Dry density
ρ_i	Immediate settlement
ρ_s	Particle density
ρ_{sat}	Saturated density
ρ_w	Density of water
σ	Total normal stress
σ'	Effective normal stress
σ'_a	Total, effective axial stress
σ'_e	Equivalent consolidation pressure (one-dimensional)
σ_r, σ'_r	Total, effective radial stress
$\sigma_{stb;d}$	Eurocode 7 design value of stabilising total vertical stress
σ'_v	Effective overburden pressure
$\overline{\sigma'_v}$	Average effective overburden pressure
σ_1, σ_2, σ_3	Total major, intermediate and minor stress
$\sigma'_1, \sigma'_2, \sigma'_3$	Effective major, intermediate and minor stress
τ	Shear stress
ϕ'	Angle of shearing resistance with respect to effective stresses
ϕ_{cv}	Critical state, or constant volume, angle of shearing resistance
$\phi_{cv;d}$	Design value of critical state angle of shearing resistance
ϕ'_d	Design value of ϕ'
ϕ_u	Angle of shearing resistance with respect to total stresses (=0)
ψ	Angle of back of wall to horizontal, Eurocode 7 correlation factor

About the Companion Website

The book's companion website www.wiley.com/go/smith/soilmechanics10e provides you with resources and downloads to further your understanding of the fundamentals of soil mechanics and the use of Eurocode 7:

- A suite of editable spreadsheets which map onto the worked examples in the book, showing how they are solved.
- Solutions to the end-of-chapter exercises, including the full workings and accompanying spreadsheets.
- Convenient tables with useful data and formulae.
- Animations to demonstrate some of the more complex laboratory testing and geotechnical procedures.

Part I

Fundamentals of Soil Mechanics

Chapter 1

Classification and Physical Properties of Soils

Learning objectives:

By the end of this chapter, you will have been introduced to:

- the formation of rocks and soils;
- clay soils and the field identification of soils;
- the classification of soils;
- various physical properties of soils and the relationships between them.

In the field of civil engineering, nearly all projects are built on to, or into, the ground. Whether the project is a structure, a roadway, a tunnel, or a bridge, the nature of the soil at that location is of great importance to the civil engineer. *Geotechnical engineering* is the term given to the branch of engineering that is concerned with aspects pertaining to the ground. *Soil mechanics* is the subject within this branch that looks at the behaviour of soils in civil engineering.

Geotechnical engineers are not the only professionals interested in the ground; soil physicists, agricultural engineers, farmers and gardeners all take an interest in the types of soil with which they are working. These workers, however, concern themselves mostly with the organic topsoils found at the soil surface. In contrast, geotechnical engineers are mainly interested in the engineering soils found beneath the topsoil. It is the engineering properties and behaviour of these soils, which are their concern.

1.1 Agricultural and engineering soil

If an excavation is made through previously undisturbed ground the following materials are usually encountered (Fig. 1.1).

Topsoil

A layer of organic soil, usually not more than 500 mm thick, in which humus (highly organic partly decomposed vegetable matter) is often found.

Smith's Elements of Soil Mechanics, 10th Edition. Ian Smith.

Companion website: www.wiley.com/go/smith/soilmechanics10e

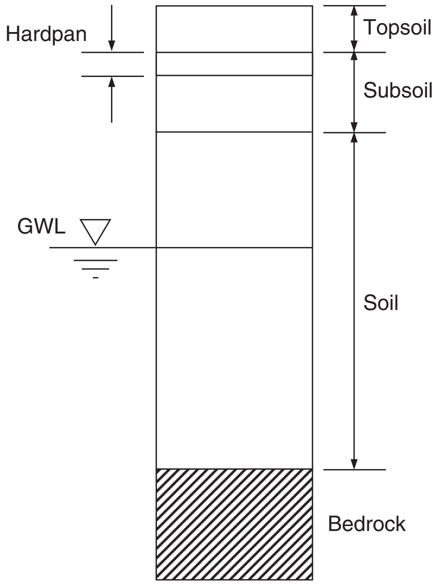

Fig. 1.1 Materials encountered during excavation.

Subsoil

The portion of the Earth's crust affected by current weathering and lying between the topsoil and the unweathered soil below.

Hardpan

In humid climates, humic acid can be formed by rainwater causing decomposition of humus. This acid leaches out iron and alumina oxides down into the lower layers where they act as cementation agents to form a hard, rock-like material. Hardpan is difficult to excavate and, as it does not soften when wet, has a high resistance to normal soil drilling methods. A hardpan layer is sometimes found at the junction of the topsoil and the subsoil.

Soil

The soft geological deposits extending from the subsoil to bedrock constitute soils. In some soils, there is a certain amount of cementation between the grains, which affects the physical properties of the soil. If this cementation is such that a rock-hard material has been produced, then the material must be described as rock. A rough rule is that if the material can be excavated by hand or hand tools, then it is a soil.

Bedrock

Beneath the soil, rock is encountered. This rock is often referred to as *bedrock* and the horizon at which the soil meets the rock is known as the *rockhead*.

Groundwater

A reservoir of underground water. The upper surface of this water may occur at any depth and is known as the *water table* or *groundwater level* (GWL).

1.2 The rock cycle

Rocks and soils are formed within a geological process known as the *rock cycle* (Fig. 1.2). The process is continuous and has lasted for millions of years.

1. Magma (molten rock) rises towards the surface, cooling and solidifying along the way.
2. The magma crystallises beneath or above the Earth's surface forming igneous rocks.
3. At the surface, rocks undergo physical and chemical weathering which break down the parent rock into particles.
4. The rock particles (sediments) are moved downslope and transported by glaciers, rivers and wind. The combined processes of weathering and transportation are referred to as *erosion*.
5. Eventually the sediments are deposited in oceans and floodplains, where they undergo *lithification*: the process where the particles are compressed under great pressure over time to form rock.
6. Sedimentary rocks are formed.
7. If the sedimentary rock is subjected to further great pressures and heat, it will react and change to a metamorphic rock.
8. Metamorphic rocks subjected to very high pressure or temperature, liquefy into magma that eventually crystallises into igneous rock, and the cycle starts again.

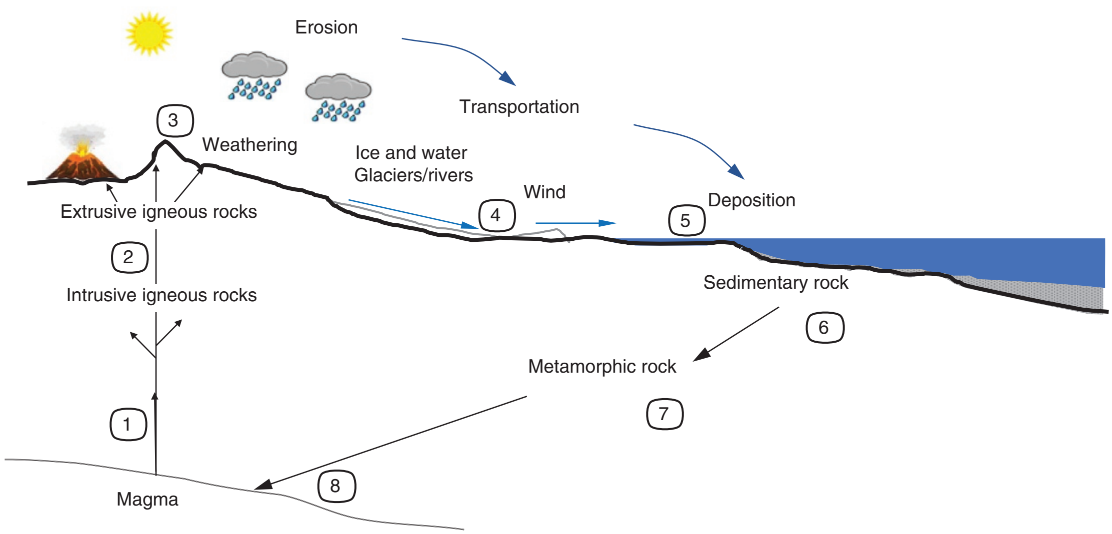

Fig. 1.2 The rock cycle.

1.2.1 Rock

Rocks are made from various types of minerals. Minerals are substances of crystalline form made up from a particular chemical combination. The main minerals found in rocks include quartz, feldspar, calcite and mica. We can classify all rocks into three basic groups: *igneous*, *sedimentary* and *metamorphic*. The position of each within the rock cycle is shown in Fig. 1.2.

Igneous rocks

These rocks have become solid from a melted liquid state. *Extrusive* igneous rocks are those that arrived on the surface of the Earth as molten lava and cooled. *Intrusive* igneous rocks are formed from magma that forced itself through cracks into the rock beds below the surface and solidified there.

Examples of igneous rocks: *granite, basalt, gabbro*.

Sedimentary rocks

Weathering reduces the rock mass into fragmented particles, which can be more easily transported by wind, water and ice. When dropped by the agents of weathering, they are termed *sediments*. These sediments are typically deposited in layers or beds called strata and when compacted and cemented together through lithification, they form sedimentary rocks.

Examples of sedimentary rocks: *shale, sandstone, chalk*.

Metamorphic rocks

Metamorphism through high temperatures and pressures acting on sedimentary or igneous rocks produces metamorphic rocks. The original rock undergoes both chemical and physical alterations.

Examples of metamorphic rocks: *slate, quartzite, marble*.

Identification of rocks

The identification of rocks may, initially, be considered quite a tricky thing to get right. With practice and experience however, engineers and geologists can rapidly identify features, that enable the identification to be made swiftly. Features, which assist in the identification and description of the rock type, include colour, grain size, mineralogical composition, structure and void content. Guidance on the identification and description of rock types is given in BS EN ISO 14689 (BSI, 2018b) and in the *Code of practice for ground investigations*, BS 5930 (BSI, 2015).

1.2.2 Soil

The actions of frost, temperature, gravity, wind, rain and chemical weathering are continually forming rock particles that eventually become soils. There are three types of soil when considering modes of formation.

Transported soil (gravels, sands, silts and clays)

Many soils have been transported by water. As a stream or river loses its velocity, it tends to deposit some of the particles that it is carrying, dropping the larger, heavier particles first. Hence, on the higher reaches of a river, gravel and sand are found whilst on the lower or older parts, silts and clays predominate, especially where the river enters the sea or a lake and loses its velocity. Ice, in the form of huge slow-moving yet