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Richard E. Jackson
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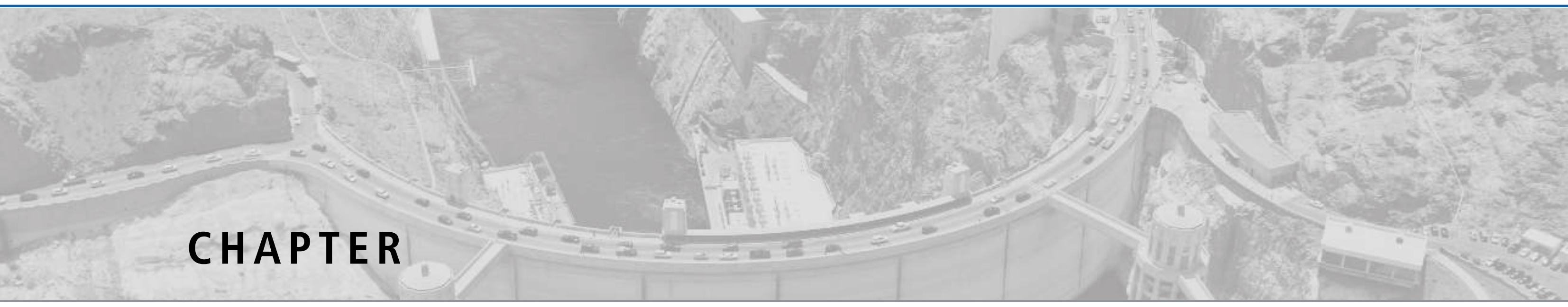

CHAPTER

# 1 Introduction

This introductory chapter considers the nature of the collaborative work of geotechnical engineers and geoscientists in project teams. This requires defining the various disciplines involved and the competencies expected of engineers and geoscientists working on geotechnical problems. Secondly, we introduce the terminology of the geosciences and those concepts that are foreign to most engineering thinking, e.g., endless time, heterogeneity of materials and the importance of discontinuities in those materials. We conclude this chapter with a review of certain elementary ideas and principles of analysis that will be found throughout the book, e.g., Amonton's law, Mohr's analysis of stresses, elasticity and Hooke's law, Terzaghi's principle of effective stress and Darcy's law. Terms appearing in **bold** should be memorized.

## 1.1 An Introduction for Geotechnical Practice

The relationship between geotechnical engineers and engineering geologists, who are often their team partners, has been a matter of concern in the USA (Sitar, 1985), Canada (Hungr, 2001), Europe (Bock, 2006) and in particular the UK (Knill, 2003). This concern has often to do with the roles that geotechnical engineers and engineering geologists play in particular projects and how they act collaboratively. Schematics that show the roles played by geotechnical engineers – those practicing rock mechanics and soil mechanics – and engineering geologists usually involve a triangular relationship of mutual interdependence. But in the UK, John Knill (2003), late Professor of Engineering Geology at Imperial College in London, wrote of his regret that engineering geology was not considered by geotechnical engineers as being of equal importance to them as were soil and rock mechanics. If Knill was correct – and correct perhaps not just with respect to the UK – then it is likely that geotechnical project managers have failed to heed the wisdom of the founders of geotechnical engineering. For example, Karl Terzaghi (1961) wrote of himself that "as his experience in the practical application of soil mechanics broadened, he realized more and more the uncertainties associated with the results of even the most conscientious subsurface explorations. The nature and importance of these uncertainties depend entirely on the geological characteristics of the sites". Here then Terzaghi points to one cause of failure in the design of infrastructure, i.e., the complexity of geological phenomena even at the site scale.

Geotechnical teams must be carefully balanced and skillfully led while maintaining the flow of information between members during site characterization, experimental testing and numerically based design. Box 1.1 presents some definitions of the various professions that work in the geotechnical field. As a geotechnical or geoenvironmental engineer, it is most likely that your work will involve project teamwork with one or more of these professional disciplines throughout your career. A former aerospace engineer, James Adams of Stanford University, notes this about design teams: "The team must be large enough to include the necessary knowledge and skills but small enough to take advantage of the high quality of communication, creativity, and motivation found in small work groups … there is no more rewarding job than being part of a motivated multidisciplinary design team working on a challenging and important product" (Adams, 1991).

According to John Burland (2012b), Emeritus Professor of Geotechnical Engineering at Imperial College, "four distinct but interlinked aspects", presented in Figure 1.1, define geotechnical practice:

 

**BOX 1.1 PROFESSIONAL DISCIPLINES PRESENT IN GEOTECHNICAL PROJECT TEAMS**

*Engineering geology*: Application of geological principles to obtain information and understanding of geological structures, materials and processes, as needed for engineering analysis and design.

*Environmental geology*: Application of geology to obtain information and understanding of geological structures, materials and processes, as needed for the solution of environmental problems. There is much overlap with engineering geology.

*Geoenvironmental engineering*: Application of geological and engineering sciences to the solution of environmental problems, such as the design of sanitary landfills, industrial waste disposal facilities and other infrastructure associated with public health and environmental protection.

*Geological engineering*: Application of geological and engineering sciences to the analysis and design of soil, rock and groundwater resources. In North America, geological engineers act as a bridge between geotechnical engineers and geoscientists and often are licensed as both engineers and geoscientists.

*Geomorphology*: Application of geological and engineering principles to understand erosion and sedimentation leading to the creation of distinct landforms and to the description of rivers and floodplains. Engineering geomorphology is a field that has developed in the UK and is in its infancy in North America.

*Geotechnical engineering*: Application of the science of soil mechanics, rock mechanics, engineering geology and other related disciplines to engineering and environmental projects (after Morgenstern, 2000). The word *geotechnical* is often used to indicate all applied earth science, including engineering or geoscience, e.g., the Canadian Geotechnical Society. The title of this box shows an example of this broad use of the word.

*Hydrogeology*: Application of geological and engineering principles to the characterization of the hydraulic properties of geologic materials, the assessment of groundwater resources and their protection from contamination.

*Source*: Modified from Hungr (2001).

1. the ground profile, including groundwater conditions;
2. the observed or measured behaviour of the ground;
3. prediction using appropriate models; and
4. empirical procedures, judgement based on precedent and "well-winnowed" experience.

The ground profile, sometimes referred to as the "ground model" or geological model by engineering geologists and hydrogeologists, is the site description in terms of the soil and/or rock layers and the groundwater conditions as they vary across the site with careful acknowledgement of the boundary conditions. Burland notes that "nine failures out of ten result from a lack of knowledge about the ground profile – often the groundwater conditions". A Joint European Working Group (Bock, 2004) of geotechnical engineers and geologists defined the ground model as "the project specific idealisation of the ground incorporating the principal elements of the geological model and the relevant engineering parameters and material properties of the ground".

The observed or measured behaviour includes both laboratory testing of samples of soil and rock, and field testing to determine their hydraulic and mechanical properties. It also encompasses field observations of ground motion, groundwater flow or contaminant migration. Most recently it has come to include measurements of ground movement or topographic elevation by Earth-orbiting satellites.

The use of appropriate analytical and numerical models to simulate the distribution of stresses in rocks, the stability of slopes along transportation corridors, groundwater flow and contaminant transport near waste-disposal facilities, etc. has become central to geotechnical and geoenvironmental engineering. These models idealize the properties of the geological materials to allow the engineer to assess the likely behaviour of rock masses, soil slopes and pollutant plumes. It is vital that the engineer understands the limits of reliability of these models, which are usually determined by our imperfect knowledge of these properties and their spatial variability. Predictions must be validated and assessed by the engineer through other means, e.g., comparison with simpler solutions, laboratory experiments or previous experiences. In fact, before the engineer undertakes simulations of any great complexity, it is essential to have developed numerous "back-of-the-envelope"

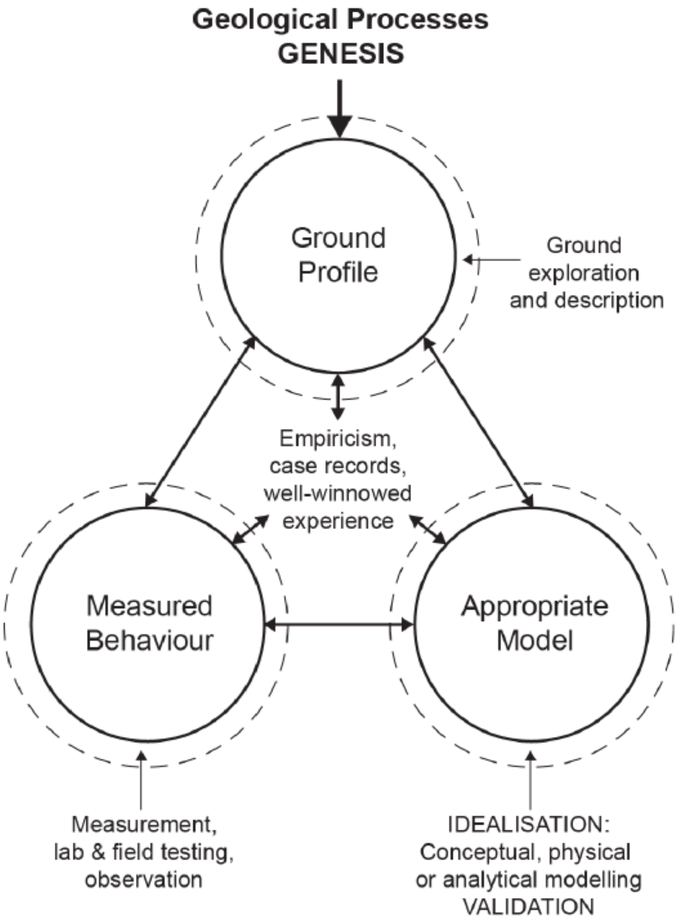


**Figure 1.1** Burland's geotechnical triangle. Each activity has its own distinct methodology and rigour. Good geotechnical engineering requires that the triangle is always kept in balance. The "model" is an idealization that is validated by consideration of the observed behaviour of materials at the site and by the ground profile, including the groundwater conditions and their variation across the site. In developing each node of the geotechnical triangle, the engineer should consider precedent, empiricism and "well-winnowed" experience. In Burland's words: "to analyze is to first idealize". (Reproduced from Burland (2012b) with the permission of the author.)

estimates of the problem under consideration so that the general domain of reasonable results is understood.

Burland's (2012b) final recommendation was to use "well-winnowed experience", i.e., that which has been continually refined by trial and error with respect to a particular procedure, or to employ an appropriate case history. One particular procedure – the observational method – was described by the late Ralph Peck, formerly of the University of Illinois (Peck, 1969). It stresses the critical need to continue the design process during construction so that modifications can be made to ensure satisfactory performance. This procedure involves careful examination of the soil and rock conditions that are actually encountered as well as monitoring ground movements or water levels and comparing both with those anticipated during the design process. Thus, precedent, empiricism, experience and risk management are at the centre of what is referred to as Burland's geotechnical triangle.

Box 1.2 defines the professional competencies of geotechnical engineers as defined by the same Joint European Working Group mentioned above. The geotechnical engineer is assumed to understand the application of specialized testing methods to estimate parameters as well as the constitutive laws governing the behaviour of materials. He or she must be able to design geotechnical structures on the basis of a ground or site characterization model using appropriate numerical methods and tools. It is the engineering geoscientist's role (see Box 1.3) to specify the nature of site conditions and combine them into a geologic model that complements the ground model. This geologic model will employ a full range of modern mapping techniques, such as geographical information systems and digital photogrammetry.

## 1.2 An Introduction to the Applied Earth Sciences

There are not many geotechnical engineers who have earned PhDs in both geotechnical engineering and geology. One such person is Roland Pusch, formerly a Professor of Soil and Rock Mechanics in Sweden. In his introduction to *Rock Mechanics on a Geological Base*, Pusch (1995) notes "that many geologists have an education that does not make them able to fully understand technico-geological issues. The engineer should therefore have [his/her] own insight in geology that is sufficient to take geological features into consideration and to interpret the rock description given by geologists". We may translate "technico-geological" to read "engineering geological" issues. Unfortunately for the engineer, geology has acquired a huge vocabulary of terms that is utterly daunting at first sight. The handy paperback *Dictionary of Geological Terms* has 8000 terms that are in relatively common use and is a valuable reference for any engineer's bookshelf. Like it or not, if we are to heed Pusch's recommendation, we must plunge into this massive vocabulary in order to gain our own insight.

### 1.2.1 Basic Geological Terms

Atoms, which are just a few tenths of a nanometre in diameter, form mineral crystals that may grow to 1 mm or longer. These crystals form the basic building blocks of soil grains and rocks.

### BOX 1.2 PROFESSIONAL COMPETENCIES OF GEOTECHNICAL ENGINEERS

*Specialised testing methods*: The engineer is expected to understand the use and reliability of (1) such test instruments as the oedometer to measure soil consolidation, and triaxial testing machines for measurement of compressive strength and elastic moduli of rocks, and (2) field procedures such as slug tests to measure hydraulic conductivity.

*Constitutive laws*: These laws are invoked in the idealization of all aspects of material behaviour, including soils, rocks and fluids (groundwater, soil gas, oil). The engineer must understand the nature of each to identify the appropriate constitutive law. Complications arise due to the heterogeneity of geological materials, e.g., bedding and schistosity cause scale and orientation dependencies of the geological materials.

*Numerical modelling of complex geotechnical structures*: Such models must accommodate complex constitutive laws and the large spatial variability of the critical parameters in geological materials.

*Size of the ground model and boundary conditions*: Each geotechnical model requires that the boundaries be fully defined between the part of the ground affected by the engineering structure ("near field") and those parts unaffected by it ("far field") where the natural geological conditions prevail. This will require liaison between the engineer and engineering geologist so that the size of the ground model and the nature of the boundaries are well defined in terms of geomechanical and hydraulic properties and geological variability.

*Uncertainty*: Because of the above, uncertainties will always exist in geotechnical and geoenvironmental projects. Engineers cope with these uncertainties by specially adjusted site characterization, design, construction and contractual procedures. For example, the "observational method" involves the collection of observation and performance monitoring data during construction to allow the implementation of preconceived geotechnical design alternatives. Consequently, the design process continues throughout the construction period because the properties of the site are uncertain within bounds.

*Source*: After Bock (2004).

Rocks are therefore aggregates of minerals, such as silicates, sulfates, carbonates and oxides, the study of which is known as **mineralogy**. Why should a geotechnical engineer concern him- or herself with the mineral composition of rock? Pusch indicates that there are five principal reasons:

1. for estimating the wearing of drilling bits due to high quartz content;
2. for structural characterization of rock material with respect to the presence of zones of weak minerals, such as mica and chlorite bands;
3. for judging the sensitivity of a rock to chemical degradation by heat or dissolution (sulfates, chlorides and feldspars), or to mechanical degradation upon compaction of rockfill (richness in mica);
4. for identification of weathering that causes slaking or expansion on exposure to water, e.g., clay minerals; and
5. for estimating the mechanical properties of discontinuities (rock fractures) that are commonly coated or filled with minerals with special properties, e.g., chlorite, graphite and clay minerals.

The presence of quartz in rock indicates costly drilling operations due to prematurely worn drill bits. But quartz in rock aggregate makes asphalt more slip-resistant. Several of the minerals mentioned by Pusch are considered layer silicate minerals, e.g., mica, chlorite and clay minerals, which are insoluble but lack the strength of quartz. Clay minerals are perhaps the most important class of minerals in geotechnical and geoenvironmental engineering in that their presence is associated with heaving soils, ruptured pavements and slope instabilities. The mineral structure of others, e.g., sulfates and chlorides, is such that they weather readily when exposed at the surface; that is, they tend to break down and lose strength. To Pusch's list we might add metal sulfides, e.g., pyrite, whose weathering is the cause of **acid-rock drainage**, which occurs when pyrite-bearing shales and mudrocks are exposed to oxidation at the ground surface.

The description and classification of rocks by microscopic examination of thin sections of rock is known as **petrography**, while **petrology** deals with the origin, occurrence, structure and history of rocks. Thus a geotechnical engineer might request a petrographic analysis of a sample of rock that is

**BOX 1.3 PROFESSIONAL COMPETENCIES OF ENGINEERING GEOLOGISTS**

*Synthesis of fragmentary information into models*: Engineering geologists bring an understanding of geological processes to bear in interpreting landforms, structures and geological materials in the site context. This allows them to develop geological models that synthesize diverse and fragmentary data from geological, geomorphological, hydrological, geotechnical and geophysical site data.

*Training for site-related work*: Engineering geologists are trained in fieldwork and the acquisition of information that such work produces. Thus engineering geologists can discern features in a landscape that are important in geotechnical engineering and may be unseen by the engineer.

*Versatility in handling maps, aerial photos and GIS data*: An engineering geologist is capable of employing and interpreting three-dimensional and time-variable data using classical geological maps as well as modern information technologies such as geographical information systems (GIS), digital photogrammetry and remote sensing systems, e.g., LiDAR.

*Observation and analysis of geological data to minimize contractual disputes*: Contractual disputes leading to litigation, excess costs and project delay have become familiar aspects of geotechnical projects. The training of engineering geologists permits them to observe, identify, describe and classify geological and technical phenomena in the field and on the construction site and then to provide objective interpretations of the data collected.

*Familiarity with fractured and weathered materials*: Rocks and overconsolidated soils are geological materials that are typically fractured by joints or faults or show signs of weakness due to long-term weathering. Engineering geologists have developed methods for characterizing these materials and features that serve the needs of geotechnical engineers.

*Source*: After Bock (2004).

to form the foundation of a structure after having referred to reports on the structural geology and petrology of this rock formation. We discuss mineralogy and petrology in Chapter 2.

We may define three principal rock types. **Igneous rocks** cool and crystallize from molten magma originating in the Earth's interior, e.g., granites and basalt. As magma intrudes into the Earth's surface, it metamorphoses those rocks already present into **metamorphic rocks**, producing gneiss and marble. Figure 1.2 shows an igneous intrusion into what was once a sedimentary rock that has been metamorphosed by the heat and stresses associated with the intrusion. Sediments originate as grains of rocks that have been weathered and have undergone erosion and transport of the eroded grains. Subsequent deposition by water, ice and wind yields **sedimentary rocks**, e.g., the sandstone, limestone and shale formations of the Grand Canyon of the Colorado River shown in Figure 1.3. Bedrock of any of these three types is often the foundation in and over which buildings, highways, pipelines, tunnels and other infrastructure are built.

A geologic structure is described by the geometry of the rocks composing it; **structural geology** deals with the geometry, spatial distribution and formation of geologic structures,

**Figure 1.2** Granitic dike and sill complex in a road cut, Serpent River, Ontario. The 2 m thick sub-vertical dike has released thin (1–5 cm) horizontal sills that have penetrated along the bedding planes of the former sedimentary rock. The dike is part of the Cutler pluton that has been dated at approximately 1740 Ma (million years before present). Rock hammer placed for scale in the fracture in the centre of the dike. (Information courtesy of R.M. Easton, Ontario Geological Survey.)

**Figure 1.3** The Grand Canyon of the Colorado River, Arizona, USA. Limestones and sandstones form the cliffs while the slopes are formed from shales, which are more readily weathered.

**Figure 1.5** Fractured Precambrian siltstone, northern Ontario. Rock hammer for scale, length = 28 cm.

**Figure 1.4** Faulting in sandstone and mudstone, Torrey Pines State Beach, San Diego, California.

in particular faults and folds in rocks. **Faults** are fracture zones along which there has been displacement of one side relative to the other parallel to the fracture, as shown in Figure 1.4, while **folds** are the deformed curved features created from an otherwise planar structure. These geological structures are the result of **tectonic forces**, which are those external and usually regional processes that create a set of structures within a particular region. Their importance will be examined in Chapter 3.

We must differentiate between **intact rock**, the **fractures** or **discontinuities** that may be contained within it and the **rock mass** as a whole. Figure 1.5 shows a fractured rock mass of siltstone that forms an **outcrop**, i.e., it is visible at the Earth's surface. Intact rock is that which has no through-going fractures, which effectively reduce the tensile strength of the rock mass to zero. At a very small scale, approximately half the length of the rock hammer shown or about 15 cm, there are blocks of intact rock, which may be individually characterized on the basis of their density, deformability and strength. But quite clearly the outcrop shown is heavily fractured and the sum of intact rock plus the fractures constitutes the rock mass. The difference between the two terms – fractures and discontinuities – is a subtle one and their influence is discussed in Chapters 4 and 11.

Where, then, is the division between soil and rock? We shall follow Morgenstern's (2000) advice in which soil differs from rock by disintegrating when submerged in water. The term **soil** is one which requires some careful consideration because of its different meaning to geologists, soil scientists and engineers. The *Dictionary of Geological Terms* gives two definitions for soil: "1: the natural medium for growth of land plants; 2: in engineering geology, all unconsolidated material above bedrock". The first definition is essentially that of soil scientists, while the second is that of geotechnical engineers. In soil science, the soil profile is a characteristic sequence of unconsolidated materials each of which was generated by specific and well-understood soil development processes, which we shall discuss in Chapters 6 and 7. Residual soils are those that have developed in place from **weathering** (i.e., the physical and chemical degradation of rocks and minerals), whereas transported soils are those that have been transported by gravity, water, wind or ice. The geologist more precisely refers to the former as "soil" and the latter as "sediment".

**Figure 1.6** Fluvial gravels: the ingredients of a future conglomerate, Uranium Road, western Colorado. Hammer for scale. Some of the gravel pore spaces have been infilled by sand and mud, yielding a lower porosity and permeability but providing the cementing agents to convert the gravel to a conglomerate. The gravel is well rounded, as in a typical conglomerate, due to extensive abrasion in the stream that transported and then deposited it. Needless to say, this material is difficult to drill into and even more difficult to collect a sample of.

How did these differences in use develop? Perhaps it goes back to 1926 when many of the principles in Terzaghi's *Erdbaumechanik auf Bodenphysikalischer Grundlage*, which Goodman (1998) translates as *Earthwork Mechanics based on the Physics of Soils*, were translated in the USA in abbreviated form to be published as *Principles of Soil Mechanics, a summary of experimental studies of clay and sand.* We shall adhere to the meaning given to "soil" by engineering geologists and geotechnical engineers, i.e., *all unconsolidated material above bedrock*, but use **sediment** in the geological sense in conjunction with a genetic term, e.g., fluvial sediments, glacial sediments, so that the sense of solid grains and particles transported and deposited by water, wind, ice or by chemical precipitation is maintained because the mode of genesis is vitally important to the material properties. Rather than merely describing the materials as sediments, we often define them by their texture, therefore Figure 1.6 shows some fluvial gravels in western Colorado (USA), while Figure 1.7 illustrates free-standing eolian, or wind-transported, silts in eastern Washington (USA).

**Figure 1.7** Wind-blown silt, an eolian sediment, photographed near Walla Walla, Washington state, USA.

This introduction to basic geological terms will suffice for the rest of this chapter. We will deepen our understanding in Part I as we consider mineralogy and petrology (Chapter 2), geological structures and maps (Chapter 3), elementary rock mechanics (Chapter 4) and the characterization of rock masses (Chapter 5). However, first we need to consider issues concerning geological space and time and the understanding of geological processes.

### 1.2.2 Heterogeneous Materials and the Representative Elementary Volume

Consider the following observation of Roland Pusch (1995): "the entire physical behavior of rock masses depend on their heterogeneity and it is becoming increasingly clear that the various discontinuities are responsible for the scale-dependence of all practically important bulk properties". The **discontinuities** referred to here are those associated with joints, fractures and faults, i.e., any discontinuous feature in an otherwise continuous rock mass that has no tensile strength, for example, the sets of fractures in the siltstone shown in Figure 1.5.

Heterogeneity in geological materials is a fact of life that makes them quite different from other materials that other engineers deal with, e.g., concrete, steel, silicon, polymer. This issue of heterogeneity, and in particular the expense of characterizing the heterogeneous properties of soil and rock, means that geotechnical and geoenvironmental engineers operate under very different constraints than do structural, mechanical or chemical engineers. It is typically the role of engineering geologists, hydrogeologists and geological engineers to specify the nature of this heterogeneity so that engineers might proceed with their designs. In so doing, we must introduce the concept of the **representative elementary volume** (REV).

The determination of an REV of soil or rock is required to analyze any problem involving stress and strain in geomechanics and fluid flow and pore volume in hydrogeology. For example, if we are concerned with defining the minimum volume of soil or rock that will provide a reliable parameter estimate of porosity, then sample size is important. Below a certain sample size, the variations in the measured porosity estimate fluctuate considerably – see Figure 1.8. The smallest volume sampled may give a porosity of 1 if the point sampled is within a pore. However, if the sampling point is part of a sand grain bounding the pore, then the porosity value is 0. Thus any domain that constitutes an REV must contain both a solid portion and a void space that may be filled by some water or gas.

Bear (2018) provides an extensive discussion of the REV concept and its role in quantifying fluid transport in continuum (fluid and solid) mechanics. He indicates that the size of the REV that is selected for analysis must meet the condition that “the average value at a point should remain, more or less, constant over a range of REV volumes that corresponds to the range of variation in the sample size, or in the instrument that monitors that average”.

As shown in Figure 1.8, with the increasing volume of porous media sampled, the measured value of porosity begins to stabilize towards a representative or mean value. For sandy soils, a volume with a radius of 10 to 20 grain diameters may define the average volume, while petroleum engineers think of 100–1000 grain diameters for sandstones. However, if the sample size becomes too large, it is possible that the porosity estimate may again begin to show variability because of a textural change, i.e., the sample volume is so large that an adjacent soil or rock mass has become part of the sample, and the sample becomes inhomogeneous or heterogeneous. Quite obviously the REV is also strongly influenced by the presence of discontinuities as well as textural changes. Ultimately the use of the parameter must constrain how the REV is determined.

Other examples of geomechanical and hydrogeological parameters that require consideration of the REV are rock strength, stress and hydraulic conductivity. For structural geologists, a critical consideration is the representative elementary *area* (REA) that adequately describes the distribution of forces acting on any surface within a rock mass. Thus an REA will provide a meaningful average of the surface forces in the rock mass such that heterogeneities in stiffness and width of mineral grains do not unduly bias the measurement (Pollard and Fletcher, 2005).

We conclude that sample size is always an important consideration in testing specimens during laboratory analysis or *in situ* testing in the field. For example, the uniaxial strength of rock pillars in a mine is known to be a function of the sample

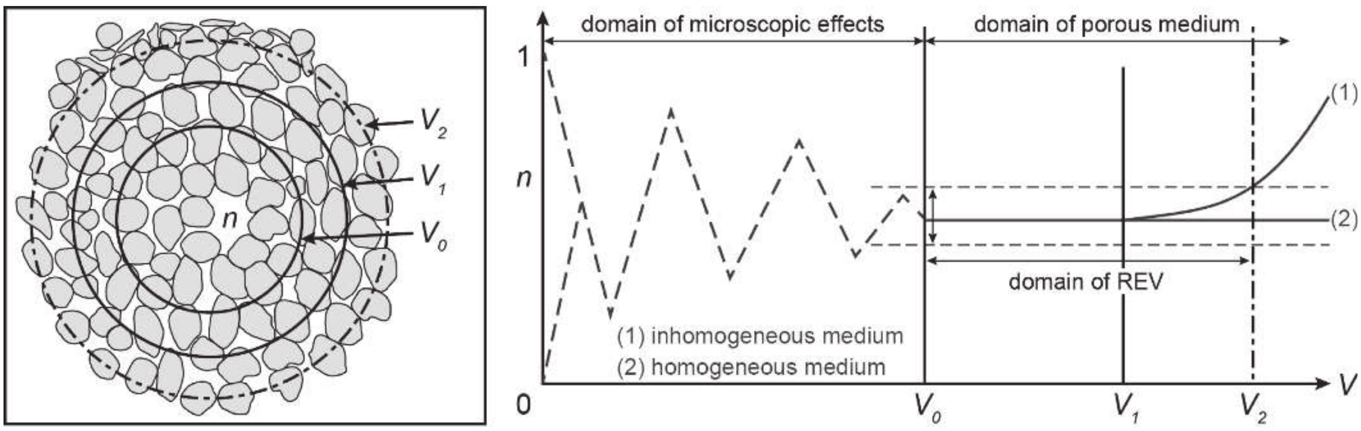


**Figure 1.8** The REV of porosity ($n$) in a soil defined as existing only between $V_0$ and $V_2$. (Figure based on Bear (1972); reproduced with permission of Jacob Bear, Elsevier and Dover Books.)

size, such that the strength may decrease to 20–30% of its maximum over a distance of 1 m in sample size (Wyllie, 1999).

### 1.2.3 Rates of Geologic Processes

Geologic processes have occurred over a vast sea of time, which will be discussed in Chapter 2. However, this immense time scale of over four billion (i.e., 4000 000 000) years means that what appear to be slow rates of change accumulate over time to result in impressive changes in the Earth's surface. Consider the following:

- The San Andreas Fault Zone in central California appears to be slipping at an average rate of about 35 mm/yr (Hough, 2002), less so in southern California. At that rate, about 16 million years ago the block containing the Pacific coast of San Francisco would have been at the latitude of Los Angeles.
- During the last Ice Age, about 40 000 years ago, Scandinavia was ice-covered to a depth of 2–3 km. When the present Interglacial period began about 10 000 years before present and the ice retreated, the surface of the Earth rebounded approximately 500 m. This is the elevation of raised beaches that were once at sea level. This isostatic rebound of Scandinavia due to a post-glacial uplift is approximately 20 mm/yr over the last 10 000 years whereas in Scotland it has been only 1 mm/yr during this period. Rates in eastern Canada have varied from 1.5–3.5 mm/yr during the Last Glacial Maximum 18 000 years before present to 0.5–1.3 mm/yr at present (Anderson et al., 2007).
- The Grand Canyon of the Colorado River in Arizona is interpreted to have eroded to its present geometry over a period of 4–5 million years. Its maximum depth is 1829 m and thus the rate of erosion of the Canyon is about 400 mm/yr or 400 m every million years. This is much more rapid than elsewhere in the world because of the steep hydraulic gradient and the large volumes of flow entering the Canyon following snowmelt in the Rocky Mountains. The Mississippi River Basin has an annual erosion rate of only 10 m per million years (Mathez and Webster, 2004).

These rates are averages determined from processes operating over a known time period with known displacements. They might not be representative of instantaneous rates. For example, the rise in sea level during the twenty-first century appears to be much higher than during the previous century because of global warming. Thus, a long-term average is inappropriate to estimate the future rise in sea level, which appears to be of the order of 3 mm/yr.

These are examples of geological processes with implications for infrastructure construction and damage. Such rate estimates allow us to consider the consequences and plan accordingly. For example, it is anticipated that every centimetre of sea-level rise will cause the loss of approximately 1 m of sandy beach. Given the hectic pace of beach-front construction in the USA over the past few decades, the consequence of this process is severe and indicates that coastline protection will become a major issue along the US East and Gulf coasts this century.

## 1.3 Elementary Principles

How is an engineer to develop a deep appreciation for geological materials and insight into geophysical processes? Here we use "geophysical" in the broadest sense of the term, i.e., the physical study of the Earth rather than the specific and more limited use of the term as in seismic exploration. There is no better point of departure than that presented by Norbert Morgenstern (2000) of the University of Alberta, an eminent geotechnical engineer with a profound appreciation of geology. Morgenstern has pointed out that the interactive aspects of the geotechnical method set out in Figure 1.1 can be illustrated by an origin–composition–consistency matrix of soil and rock that is presented in Table 1.1. Soil is differentiated from rock on the basis of whether it disintegrates when submerged in water, while the boundary between weak and hard rock is arbitrarily set at the compressive strength of concrete. This boundary is identified as one in which rocks will slake, i.e., disintegrate, or soften; such *weak rocks* are of great geotechnical concern and are discussed in Chapter 5.

Soils are classified as either cohesionless or cohesive. Cohesionless soils include alluvium deposited by rivers, e.g., sand and gravel, as well as calcareous and gypsiferous sands, topsoil and talus, which form slope debris. Cohesive soils include clays and glacial tills, clay-rich calcareous mud known as marl, peat and tropical laterite soils. These typically contain clay minerals and therefore exhibit plasticity. Rock flour simply comprises silt- and clay-sized particles without clay minerals and lacks plasticity. The Alberta oil sands are a particular case of cohesive sandy soils with the cohesion provided by the bitumen. Soils and sediments are the subject of Part II of this book.

If we define the compressive strength of soft rocks as that being 500 kPa to 1 MPa, then friable sandstones, mudstones, chalk and gypsum are typical soft rocks. Hard rocks generally have a compressive strength of >50 MPa, and these include sandstones, limestones, shales and igneous and metamorphic

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**Table 1.1** Geotechnical classifications of geological materials (after Morgenstern, 2000).

| Rock type ⇒ | Sedimentary | | | | | |
|---|---|---|---|---|---|---|
| **Composition ⇒** | Sandy | Clayey | Carbonate | Evaporite | Organic | Igneous |
| **Consistency ⇓** | Example | | | | | |
| Cohesionless soils | Alluvium | Rock flour | Calcareous | Gypsiferous | Topsoil | Talus |
| Cohesive soils | Oil sand | Clay + till | Marl | | Peat | Laterite |
| Soft rock | Friable sst | Mudstones | Chalk | Gypsum | Lignite | Weathered granite |
| Hard rock | Sandstone | Shale | Limestone | Potash | Coal | Granite |

Notes: Soft rock is defined by compressive strength of 0.5–1 MPa. Sst = sandstone.

rocks such as granites and gneisses. A distinguishing feature of soft rocks is their tendency to slake, i.e., break apart, and soften. In the past, it has often been thought that very hard rock was not of any geotechnical concern. However, the investigation of granites as potential nuclear waste repositories in Canada and Scandinavia has shown that even such strong rocks undergo progressive failure due to high internal stresses. We will return to this matter in Chapter 4.

Before proceeding to a discussion of geological materials and their dependence on structure, we will review some basic terms – porosity, permeability, stress, strength and stiffness – and their appearance in some fundamental laws and principles of the applied earth sciences.

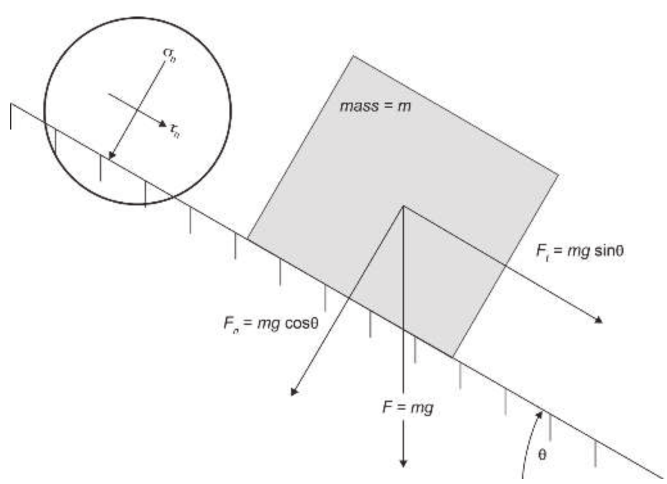


**Figure 1.9** Amonton's law: forces on an inclined plane. The inset shows the equivalent stresses. (After Turcotte and Schubert (2002); reproduced with the permission of Cambridge University Press.)

### 1.3.1 Amonton's Law of Friction

Forces and stresses in soils and rocks arise from the effects of thermal and gravitational processes. The point of departure for this discussion are the forces on an inclined plane, perhaps an unstable slope or a fracture within a rock mass, and their vectorial representation.

Figure 1.9 shows the components of force on a block of soil or rock that has just started to slide down a plane inclined at an angle $\theta$. The two components of the force ($F$) caused by this mass ($m$) are, firstly, in the downslope direction relative to the inclined plane,

$$F_t = mg \cdot \sin\theta, \tag{1.1}$$

where $g$ is the acceleration due to gravity, and secondly, acting normal to the inclined plane,

$$F_n = mg \cdot \cos\theta. \tag{1.2}$$

The resistance experienced by the block to sliding is another surface force, friction. As the inclination of the plane is increased, the frictional force per unit area ($\tau_{fs}$) at which the block begins to slide is

$$\tau_{fs} = \frac{f_s \cdot F_n}{A} = f_s \cdot \sigma_n, \tag{1.3}$$

where $f_s$ is the (dimensionless) coefficient of static friction, $A$ is the contact area and $\sigma_n$ is the normal stress exerted by the block on the inclined plane. Turcotte and Schubert (2002) refer to this as Amonton's law. They showed that $f_s \approx 0.85$ for a variety of very different rock types under drained conditions, i.e., the fluid pressure is zero. This discussion will be pursued in Chapters 14 and 15.

### 1.3.2 Mohr–Coulomb Criterion

In their introduction to the *Analysis of Geological Structures*, Price and Cosgrove (2005) present a compelling example of the importance of applied forces and stresses in rocks: