1 Geomaterials and crustal geomechanics

Geomechanics is concerned with the deformation and flow of geomaterials. A specific aspect of geomaterials, i.e. the materials that make up the planet earth, is their complex combination of solid and fluid phases.

In engineering geomechanics it is customary to talk of rock masses in a way that refers to both the rocks and the fracture systems that affect the volumes of concern. This concept, however, is often too vague for efficient mechanical modeling, and specific attention must be given to both the geomaterials and their discontinuities.

In the two first sections of this chapter we define more precisely the notion of a geomaterial and the related concept of a representative elementary volume (REV), with a brief reference to the various methods available for identifying geomaterials. In the third section we discuss the concepts of fracture sets and faults, with special attention to scaling laws. Finally, in the fourth section our attention turns to the various loading processes that may be encountered in geomechanics, whether of human or natural origin.

1.1 Rocks, soils and other geomaterials

Three kinds of rock can be identified: igneous, metamorphic and sedimentary. This characterization refers to the origin as well as to the past thermal and loading history of the rock. It implies strong consequences for the rock fabric, namely, the structure of its constitutive (solid) grains and of the complementary pore space, which is generally filled with fluid. And this introduces immediately the fact that materials of geological origin are most often multiphasic in their natural environment, i.e. they include solid, liquid and gas phases.

First, we introduce definitions that are used to describe the relative volumes occupied by the various phases. Then we introduce Goodman's classification of rocks according to their texture (Goodman, 1989), since in this book attention is given to the behavioral rather than to the genetic attributes of rocks. Such a nomenclature is helpful as a starting point for defining the material properties of import for a given mechanical problem.

1.1.1 Porosity, phase relationships, density

The representative elementary volume (REV) concept

Geomaterials always include some solid parts and some voids, the voids usually being filled with fluids, whether liquid or gas or both. The porosity of a geomaterial describes
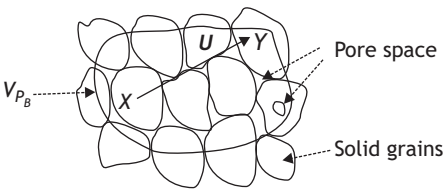
Fig. 1.1   Linear porosity.

the relative percentage of solids and voids. Let us consider a body B made up of two components, a solid component M and a fluid component F. Component M is made up of many grains that touch each other (fig. 1.1) and fluid F fills completely the voids in between the solid grains, i.e. the pore space is fully interconnected. The pore space is said to be fully interconnected when any point of it may be related to any other point of it by a continuous line, all the points of which remain within the pore space.

A small part P_B of body B, with volume V_{P_B}, includes a part P_S consisting of solid S with volume V_{P_S} and a part P_F consisting of fluid F with volume V_{P_F}, such that $V_{P_B} = V_{P_S} + V_{P_F}$. The volume V_{P_F} defines the pore space of part P_B. The *volume porosity n* of P_B is defined as $n = V_{P_F}/V_{P_B}$ while the ratio $e = V_{P_F}/V_{P_S}$ is called the *void ratio*.

The void ratio and the porosity are interrelated:

$$e = \frac{n}{1-n}, \qquad n = \frac{e}{1+e} \tag{1.1}$$

In soil mechanics, the specific volume v is defined as the total volume of soil that contains a unit volume of solid ($v = 1 + e$).

If the pore space is not fully interconnected, the volume V_{P_F} includes only the interconnected part of the total pore volume V_{P_P}. Then the fluid within the non-interconnected pore space may be different from that in the interconnected pore space, as e.g. in volcanic rocks. Furthermore, as will be discussed in section 9.3, the physical properties of the fluid that fills up the pores depend on the distance to the contact with the solid phase. For example, for water, for very small distances to the solid interface (in the micrometer range), a thin film exists that cannot flow and that can be removed only by heating up the material. It is called adsorbed water. For the purpose of defining the interconnected pore space, the adsorbed water is "assimilated" to the solid.

Let us now consider two points X and Y that define the vector U with origin at X and extremity at Y (fig. 1.1). The linear porosity $l(X, U)$ associated with the vector U at X is defined by the ratio

$$l(X, U) = \frac{|U_P|}{|U|} \tag{1.2}$$

where $|U|$ is the modulus of vector U while $|U_P|$ is the modulus of that part of $|U|$ that intersects the pore space. When point Y is the same as point X, so that $|U| = 0$, the linear porosity is set equal to 1 if point X is in a void and equal to 0 if it is located in a grain. As the modulus $|U|$ gets larger and larger, the variation in the linear porosity gets smaller and smaller (fig. 1.2) so that, for a length $|U|$ larger than, say, U^T, variations in linear porosity with increasing reference length $|U|$ may be neglected. The definition of this critical length
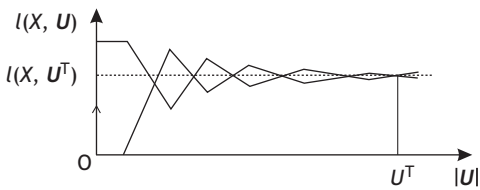
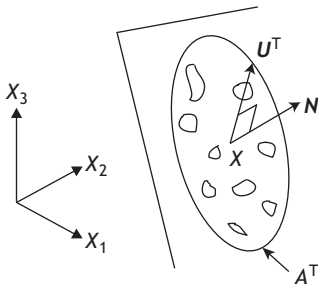**Fig. 1.2** Variation of linear porosity with the length of the defining vector $\boldsymbol{U}$.

Fig. 1.3 Areal porosity at point X in a plane with normal $\boldsymbol{N}$.

U^T is somewhat arbitrary and may be chosen so that the variations in linear porosity are smaller than, say, 0.005 or 0.001 when $|\boldsymbol{U}|$ is larger than U^T.

If the linear porosity does not vary with the orientation of $\boldsymbol{U}^T$ then it is isotropic and if it does not vary with the spatial position of X in the body, it is homogeneous.

A similar approach may be followed to define an areal porosity. Consider a planar surface with normal $\boldsymbol{N}$. The envelope of the extremities of all vectors $\boldsymbol{U}^T$ in the plane normal to $\boldsymbol{N}$ defines a closed planar contour with area A^T centered at X (fig. 1.3).

Let A_P be that part of A^T that passes through the pores. The areal porosity $f(X, N)$ at the point X in the plane normal to $\boldsymbol{N}$ is defined by the ratio

$$f(X, N) = \frac{A_P}{A^T} \tag{1.3}$$

If $f(X, N)$ does not vary with the orientation of $\boldsymbol{N}$, the areal porosity is isotropic and equal to $l(X, U^T)$.

Finally, when the dip (see fig. 1.9) of the normal $\boldsymbol{N}$ varies from 0 to π, the envelope of all surfaces with area A^T normal to $\boldsymbol{N}$ defines a volume. This volume corresponds to the smallest part P of B for which the volume porosity $n(X)$ may be defined. It is called the *representative elementary volume* (REV). For bodies with isotropic porosity,

$$l(X, U^T) = f(X, A^T) = n(X) \tag{1.4}$$

As already mentioned, when the porosity does not depend on X it is said to be homogeneous. If, however, the porosity varies in space, it is said to be heterogeneous. In general, a geomaterial is said to be heterogeneous with respect to a given property when this property varies with position in the volume under consideration.

For a body made up of various constitutive minerals or grains, the concept of the REV may be extended to define the smallest part of B that is statistically representative of the body, i.e. the smallest volume for which the characteristic properties of the body under consideration may be defined. As a rule of thumb, the REV is often considered to range somewhere between 50 and 100 times the mean dimension of the grains that make up the geomaterial.

When applicable, the REV provides a means to define an equivalent body that behaves as a continuum, in which the theory of continuous functions may be applied. Expressed in terms of probability, the concept of the REV implies a stationarity in the statistical properties of the material. This concept of a statistically representative volume is discussed further in section 1.3.3 and in chapter 10, where fracture fields are discussed and are found *not* to satisfy the concept of the REV.

Various techniques have been developed for measuring the porosity, whether based on the percolation of fluids (the mercury porosity) or by direct visual inspection of planar surfaces (Bourbié *et al.*, 1986; Guéguen and Palciauskas, 1992; Zinszner and Pellerin, 2007).

Phase relationships and density

In what follows we refer only to a representative elementary volume of material. For a completely dry geomaterial, only two phases are involved: solid and air. A fully saturated geomaterial also involves only two phases. For example, saturated soils involve solid grains and liquid water. Hence the concept of saturation refers to the idea that the pore space is filled with only one liquid. A material in which the pore space is filled with liquid and gas is described as being partially saturated. For example, a partially saturated soil has liquid water and air in the pore space. A partially saturated deep geothermal system has liquid water and vapor. However, the concept of saturation may also refer to geomaterials in which the pore space is filled with diverse immiscible liquid materials, such as brine and hydrocarbons, without any gas phase.

The moisture or water content, w, of a soil is defined as the ratio of the mass of liquid water, M_w, and the mass of solid, M_S, for an REV:

$$w = \frac{M_w}{M_S} \tag{1.5}$$

while the degree of water saturation, S_r, is defined as the ratio of the volume of liquid water, V_w, and the total pore volume, V_p, which is assumed to be fully interconnected:

$$S_r = \frac{V_w}{V_p} \tag{1.6}$$

The bulk density of a body B, ϱ_B, made up of solid S and water, is simply the ratio of the total mass of B and the total volume (see fig. 1.4):

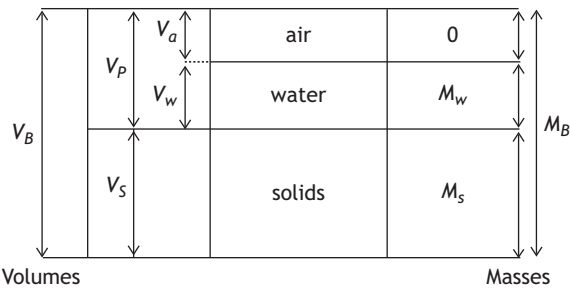$$\varrho_B = \frac{M_B}{V_B} = \frac{M_S + M_w}{V_B} \tag{1.7}$$

Fig. 1.4 The various phase relationships in masses (M) and volumes (V) for a representative elementary volume (REV) (adapted from Craig, 1987, fig. 1.10, with permission from Taylor & Francis).

If ϱ_w is the density of liquid water and ϱ_S is the density of solid, the bulk density of a saturated body B is

$$\varrho_B = (\varrho_S V_S + \varrho_w V_P)/V_B = (1 - n)\varrho_S + n\varrho_w \tag{1.8}$$

For a soil with water content w, liquid water density ϱ_w, specific gravity of solid particles $G_s = M_s/(V_s\varrho_w)$ and void ratio e, its bulk density ϱ_B is given by

$$\varrho_B = \frac{G_s(1 + w)}{1 + e}\varrho_w = \frac{G_s + S_r e}{1 + e}\varrho_w \tag{1.9}$$

When the soil is saturated, $S_r = 1$, the bulk density is

$$\varrho_B = \frac{G_s + e}{1 + e}\varrho_w \tag{1.10}$$

The mechanical properties of soils depend in particular on their particle size distribution and on their water content. For example, a dry clay may behave as a solid; yet when immersed in water it will become progressively more liquid. When the clay particles are dispersed, the density of the fluid part may be larger than that of some solid parts (e.g. those with a high unconnected pore space). These solid parts may start to float when the liquid part gets dense enough, giving rise to mud slides. Hence an uncemented clastic geomaterial may behave as a solid when its water content is low, but may behave as a dense fluid when saturated with water.

Similarly lava, which is made up of solid crystals, melted elements and gas, may behave as a fluid when the solid grains are completely dispersed in the melted part but as a very viscous solid when the solid portion dominates.

Thus the mechanical behavior of geomaterials ranges in a continuous manner from that of a solid-type material to that of a fluid-type material. For example, for soils, it depends on water saturation as well as on the void ratio and attention must be given to both these variables. Standardized tests have been devised in soil mechanics in order to define a liquid limit and a plastic limit for such soils (e.g. Craig, 1987).

More generally, geomaterials always involve diverse constituents and phases. The objective of geomechanics is to describe the deformation and/or flow of these complex systems, which cover the complete spectrum from solids to fluids. Equivalent materials are defined

in order to investigate the mechanical behavior of these systems at scales much larger than those of their representative elementary volume.

Hence, while in fact rocks are always heterogeneous because they involve various minerals and phases, the equivalent geomaterials are assumed to be homogeneous and their mechanical behavior is assumed to represent that of volumes much larger than the REV.

1.1.2 Rock and soil classification

Crystalline texture

Crystalline rocks consist of tightly interlocked crystals of silicate minerals (e.g. quartz, feldspar, micas etc.), or carbonates, sulfates or other salts. Their mechanical properties depend on those of the constitutive minerals, on those of the contact interfaces between the minerals and also on the geometry of voids between the minerals and the fluids filling up the pore space. Following Goodman, six crystalline textures may be distinguished.

Soluble carbonates and salts

These include limestone, dolomite, marble (a metamorphic limestone), rock salt and gypsum. Their mechanical properties depend strongly on the mean pressure which is applied to them. According to terminology to be introduced in the next chapter they may exhibit either an elastic or a plastic behavior, depending on their environment. Further, they, or parts of them, may dissolve in water at relatively fast rates depending on environmental conditions (time constants ranging from days to years).

Rocks with continuous bands of planar minerals

These include schists with alignments of planar minerals such as mica, chlorite or graphite schists. Mica and other sheet minerals strongly influence the mechanical properties of the rock. They are strongly anisotropic, i.e. many of their properties depend strongly on orientation.

Banded silicate minerals without mica sheets

These include gneiss. Their properties generally show some anisotropy. This anisotropy is not as strong as that of rocks with continuous bands of planar minerals yet is easily detectable by various petrophysical means.

Randomly oriented and distributed silicate minerals

Examples are granite, chlorite, gabbro, syenite etc. Their properties usually do not depend on orientation, so that they are isotropic. Chemical interaction with water is generally rather slow at low temperatures (it happens over time scales usually in thousands of years).

Randomly oriented and distributed silicate minerals in a background of very fine grains and/or glass, with vugs (small cavities)

These correspond to lava-type rocks (basalt, rhyolite etc.). The density of these materials depends strongly on the pore space, which may be very large, yet they may include many unconnected pores (i.e. each pore is completely isolated from its neighbor) that are filled with gas.

Sheared rocks

Examples are mylonites or serpentinite. Their mechanical properties are markedly anisotropic.

Clastic texture: from rocks to soils

Clastic rocks are composed of pieces of various rock types and assorted mineral grains. Their mechanical properties depend strongly on those of the cement binding the various fragments together. Five different clastic textures may be identified.

Stably cemented

Examples are silica-cemented sandstone or limonite sandstone. Examples may also be found in volcanic breccia.

With slightly soluble cement

These rocks include calcite-cemented sandstones or conglomerates. The percolation of acidic fluids rapidly modifies their properties.

With highly soluble cement

With gypsum-cemented sandstones and conglomerates, the effect of water may be very rapid (a matter of days or months).

Incompletely or weakly cemented

The difference from the two previous classes rests mostly on the quantity of the cement and is qualitative.

Uncemented: soils and granular materials

This class is described in the soil mechanics literature (e.g. Craig, 1987). It involves particles with a very wide spectrum of sizes and shapes. Particle-size analysis determines the percentage by weight of the particles within the different size ranges. The classification

distinguishes the following: clays, with particles smaller than 2 microns; silts, with particle sizes ranging from 2 microns to 60 microns; sands, with particle sizes ranging from 60 microns to 2 mm; gravels, with sizes ranging from 2 mm to 60 mm; and cobbles and boulders, containing blocks larger than 6 cm. The properties of uncemented clastic materials (often called "soils") depend strongly on their particle-size distribution. An example of grain-size analysis is shown in fig. 1.19 for the gouge of Aigion fault in the Corinth rift (western Greece).

Very fine grained rocks

These rocks include, for example, shales, slates, flagstones and marls and are made up of clays and silts with various degrees and kinds of cementation.They also include chalk and other very fine-grained materials, such as radiolarites, which result from the accumulation of plankton skeleton.

Organic rocks

These include coals and bituminous coals, oil shale and tar sand. Sometimes oil and gas are also called rock to emphasize their geological origins. According to such a definition, water would also be a rock. However, we prefer to keep the word *rock* to refer to solid material, and we introduce the more generic term *geomaterial* to refer to all materials of geological origin encountered on earth.

Hence a geomaterial may be a rock, a soil, a liquid or a gas or any mixture of these, provided that each component is of geological origin.

1.2 Rock masses and crustal geomechanics

In the previous section the concept of pore space was introduced without any consideration of the morphology of the pores. However, when discussing rock textures we mentioned that laminar minerals and their relative alignments are of great importance for the mechanical properties of the equivalent geomaterials. Similarly *fractures*, which correspond to structures for which one dimension is much smaller than either of the others, by orders of magnitude, are the most significant structuring elements of rock masses. A key question when tackling geomechanics problems is determining how to integrate fractures into the solution. Various approaches are presented in chapters 9 and 10.

We introduce in this section, and in the next, various types of rock-mass reconnaissance for identifying equivalent geomaterials and the correlated fracture field, i.e. those fractures that are dealt with explicitly as opposed to those which are included implicitly through the definition of equivalent homogeneous geomaterials.

In order to define the equivalent geomaterials filling the volumes under consideration, these volumes must be probed with various geophysical means and/or directly sampled.

1.2.1 Geophysical exploration

Engineering applications

Essentially three classes of geophysical techniques are applied for distant rock mass reconnaissance: seismic methods, electrical and electromagnetic methods and gravimetric methods. See e.g. Milsom and Eriksen (2011) for a review of geophysical reconnaissance techniques commonly used in geotechnical and environmental engineering or Sheriff and Geldart (1995) for deeper investigations as conducted for example in hydrocarbon exploration.

In seismic methods, seismic waves (mechanical vibrations) are artificially generated, and then specific receivers positioned at suitable locations record some of these seismic waves after they have traveled through the domain of interest. Exploitation of the results is based on seismic wave propagation theory, which rests on the theory of elasticity. This technique helps to identify the domains in which homogeneous materials may be defined, with particular attention to their fluid content. It also helps to identify whether the main reflecting structures are linked to the interfaces between different materials or to major fracture zones. This is briefly discussed in chapter 11.

Because hydrocarbons and most rocks are much more electrically resistant than water, various electrical and electromagnetic methods have been developed for identifying zones with high water content. These methods are also efficient for determining the clay content, given the high electrical conductivity of clays. However, such methods are not discussed any further in this book, with the exception of the borehole electrical imaging technique, specifically developed for fracture identification in boreholes.

Gravimetric techniques help to identify contrasts in density at various depths, whether these are linked to saturation or, more generally, to fluid content or to density contrasts between different geomaterials. Such techniques have also turned out to be efficient for identifying underground cavities, both man-made (mines and quarries) and natural (e.g. karstic structures).

Crustal geomaterials

Through the combined analysis of various geophysical and geochemical observations, earth scientists have progressively refined their understanding of the structure of the earth. Their analysis has identified four successive layers starting from the earth surface, namely, the lithosphere, the asthenosphere, which starts just below the lithosphere and extends down to 3480 km, the liquid core between 3480 and 1220 km from the earth's center and finally the solid inner core (e.g. Mussett and Khan, 2000); recall that the earth's radius is equal to about 6380 km). The contact between the lithosphere and the asthenosphere is characterized by a change in mechanical behavior and occurs at variable depths depending on the location on earth.

The lithosphere itself is subdivided into the crust, which extends from the earth's surface down to the Moho discontinuity, and the mantellic lithosphere, which exhibits seismic wave velocities much faster than those of the crust. The Moho discontinuity is found at depths ranging from 5 to 10 km in the oceanic lithosphere. However, its depth in the

continental lithosphere is much more variable and may be found from 20 km in thin crust down to 60 km in subduction zones (see e.g. Stein and Wysession, 2003; for further reading on the earth's structure determined from seismic wave analysis).

The crust itself is often separated into an upper crust and a lower crust, the mechanics of which is still being debated (Burov and Diament, 1995; Burov, 2010).

The object of this text book is to introduce concepts that may be applied to analyze the mechanical behavior of the upper crust, i.e. from the ground surface down to the lower limit of the zone where earthquakes occur (generally between 15 and 25 km, except in subducting zones where it can go down to 80 km). It is often referred to as the brittle crust or the seismogenic crust.

1.2.2 Borehole reconnaissance

A major difference between engineering and earth science applications of geomechanics is that in the former direct access to the rock mass is required.

Until recently the deepest borehole ever drilled was undertaken by Russian earth scientists who were hoping to reach the Moho discontinuity (Kozlovski, 1984). After a depth of 12 262 km was reached in 1989 the project was stopped because of numerous technical difficulties linked in particular to higher than anticipated temperatures (around 180 °C at a depth of 11 500 m). At the time of writing (2014), the deepest well in the world, off the Sakalin Island coast in eastern Russia reaches 12 345 m. However, most attempts at deep drilling for scientific research purposes have been to depths shallower than 9 km, and this constitutes a major difference between engineering and earth sciences applications of geomechanics.

Indeed, in all engineering applications direct access to the rock mass is possible, and this helps to obtain *in situ* characterization of the geomaterials and of the fracture field. But in many earth science applications, as in fault mechanics, information on deep geomaterials comes only through indirect geophysical investigations.

Coring

As discussed above, direct reconnaissance of a rock mass may be made through boreholes of various sizes and lengths as well as through excavation from the ground surface or through underground access (shafts or adits). In the latter case, the underground access is often exploited further by the drilling of shallow boreholes.

Boreholes may be drilled either with core recovery, i.e. the drilling operation produces in theory a continuous cylindrical core made of the various materials and fractures encountered by the drill bit, or in a destructive manner so that only cuttings are produced. Cuttings are rock particles the size of which is in the millimeter to centimeter range. They help to identify the various geological materials intersected by the borehole.

Cores, in addition to producing samples that may be tested in the laboratory, may also be used to retrieve important information on the fracture field, as will be discussed in section 1.3.1. Various indices characteristic of the fracture density are defined for engineering