CHAPTER 2

Engineering Geology

This chapter is intended to give readers a general overview of engineering geology. More detailed information should be sought in textbooks and other publications (Waltham 1994; Bell 2007).

2.1 DEFINITION

Geology is to geotechnical engineering what history is to humankind. It is the history of the Earth's crust. *Engineering geology* is the application of the science of geology to geotechnical engineering in particular and engineering in general. The same way we learn from history to avoid repeating mistakes in the future, we learn from engineering geology to improve geotechnical engineering for better design of future structures. Engineering geology gives the geotechnical engineer a large-scale, qualitative picture of the site conditions. This picture is essential to the geotechnical engineer and must always be obtained as a first step in any geotechnical engineering project.

2.2 THE EARTH

The age of the universe and of the Earth is a matter of debate. The most popular scientific views are that the universe started with a "big bang" some 15 billion years ago and that the Earth (Figure 2.1) began to be formed some 4.5 billion years ago (Dalrymple 1994), when a cloud of interstellar matter was disturbed, possibly by the explosion of a nearby star. Gravitational forces in this flat, spinning cloud caused its constituent material to coalesce at different distances from the Sun, depending on their mass density, and eventually to form planets. The Earth ended up with mostly iron at its center and silicates at the surface.

The Earth has a radius of approximately 6400 km (Jefferis 2008). The first layer, known as the crust (Figure 2.2), is about 100 km thick and is made of plates of hard silica rocks. The next layer, called the mantle, is some 2800 km thick and made of hot plastic iron silicates. The core is the third and last layer; it has a radius of 3500 km and is largely made of molten iron.

Early on, the planet was very hot and all earth materials were melted like they are on the Sun today. The cooling process started right away and has been progressing ever since. The present temperature gradient, shown in Figure 2.2, represents an average increase in temperature with depth of 15 degrees Celsius per kilometer in the crust, although the overall average is only 1 degree Celsius per kilometer. The gravity field is governed by the acceleration due to gravity (9.81 m/s^2 on the average). This gravity field generates an increase in stress versus depth, which leads to an enormous pressure at the center of the Earth of about 340 GPa. The Earth's magnetic field is created by magma movement in the core and varies between 30 and 60 microteslas; it is strongest near the poles, which act as the two ends of the Earth dipole.

The Earth is a dynamic medium that changes and evolves through major events such as plate tectonics and earthquakes. The rock plates (about 100 km thick) that "float" on the semiliquid and liquid layers below accumulate strains at various locations where they run into each other. When the stress buildup is released abruptly, the result is an earthquake. Earthquakes and other movements allow the plates to move slowly (centimeters per year) yet significantly over millions of years. For example, on today's world map South America still looks like it could fit together with Africa—because in the distant past they were in fact joined (Figure 2.3).

2.3 GEOLOGIC TIME

Geologic time is a scale dividing the age of the earth (4600 million years) into 5 eras (Figure 2.4): Precambrian (4600 million years ago [MYA] to 570 MYA), Paleozoic (570 MYA to 245 MYA), Mesozoic (245 MYA to 65 MYA), Tertiary (65 MYA to 2 MYA), and Quaternary (2 MYA to the present) (Harland et al. 1989). Each era is subdivided into periods and then into epochs (Figure 2.5). The Quaternary era, for example, is divided into the Pleistocene period and the Holocene or Recent period.

Geotechnical Engineering: Unsaturated and Saturated Soils Jean-Louis Briaud

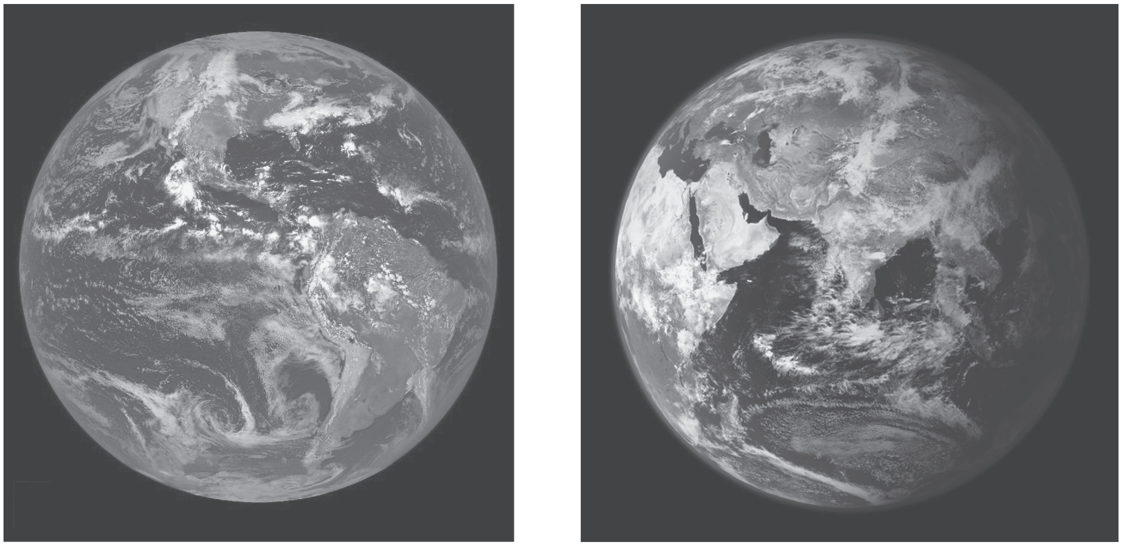

Figure 2.1 The Earth. (Courtesy of NOAA-NASA GOES Project.)

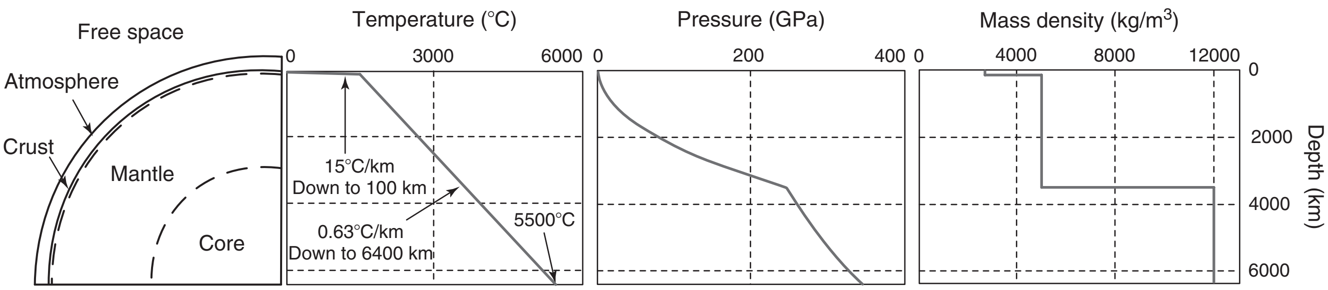

Figure 2.2 Earth temperature, pressure, and density.

Figure 2.3 South America and Africa fit. (Courtesy of John Harvey.)

Typically, the older the earth material, the stronger it is. The last Ice Age occurred about 10,000 years ago at the beginning of the Holocene period. Glaciers, some of them 100 meters thick, covered the earth from the North Pole down to about the 40th parallel (St. Louis in the USA) and preloaded the soil. Because of this very heavy preloading, called overconsolidation or OC, those soil types (e.g., till) are very stiff and strong and do not settle much under load, but may erode quickly (as in the Schoharie Creek bridge failure disaster in 1987). When the glaciers melted, the soil surface rebounded; in some places this movement is still ongoing at a rate of about 10 mm per year.

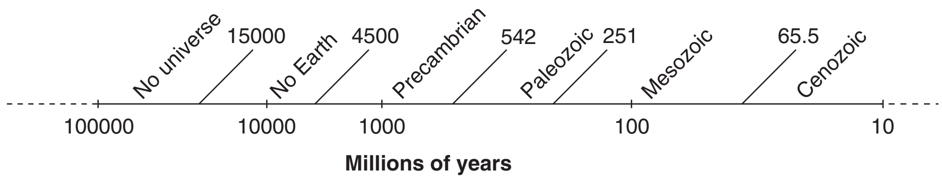

Figure 2.4 Geologic time (eras).

<table>
<tr><th colspan="3">Cenozoic ERA</th></tr>
<tr><th colspan="2">Periods</th><th>Epoch</th></tr>
<tr><td colspan="2" rowspan="2">Quaternary (Present – 2.6 My)</td><td>Holocene (present – 0.01 My)</td></tr>
<tr><td>Pleistocene (0.01 - 2.6 My)</td></tr>
<tr><td rowspan="5">Tertiary (2.6 – 65.5 My)</td><td rowspan="2">Neogene (2.6-23.0 My)</td><td>Pliocene (2.6-5.3 My)</td></tr>
<tr><td>Miocene (5.3 – 23.0 My)</td></tr>
<tr><td rowspan="3">Paleogene (23 – 65.5 My)</td><td>Oligocene (23 – 33.9 My)</td></tr>
<tr><td>Eocene (33.9 – 55.8 My)</td></tr>
<tr><td>Paleocene (55.8 – 65.5 My)</td></tr>
</table>

Mesozoic ERA
Periods
Cretaceous (65.5 – 145.5 My)
Jurassic (145.5 – 201.6 My)
Triassic (201.6 – 251 My)

Paleozoic ERA
Periods
Permian (251 – 299 My)
Carboniferous (299 – 359 My)
Devonian (359 – 416 My)
Silurian (416 – 444 My)
Ordovician (444 – 488 My)
Cambrian (488 – 542 My)

Figure 2.5 Geologic time (periods and epochs).

2.4 ROCKS

The Earth crust is 95% silica—and when silica cools, it hardens. This cooling creates the first kind of rocks: *igneous rocks*. Igneous rocks (e.g., granite, basalt, gneiss) are created by the crystallization of magma. *Sedimentary rocks* (e.g., sandstone, limestone, clay shales) are made of erosional debris on the Earth surface which was typically granular and recemented; they are created by wind erosion and water erosion, and are recemented by long-term high pressure or by chemical agents such as calcium. *Metamorphic rocks* (e.g., schist, slate) are rocks that have been altered by heat and/or pressure. The strength of rocks varies greatly, from 10 times stronger than concrete (granite) to 10 times weaker than concrete (sandstone). Older rocks are typically stronger than younger rocks. Figure 2.6 shows some of the main rock types.

2.5 SOILS

Soils are created by the exposure of rocks to the weather. This weathering can be physical (wetting/drying, thermal expansion, frost shatter) or chemical (solution, oxidation, hydrolysis). The elementary components of rocks and soils are minerals such as quartz and montmorillonite. Some minerals are easier to break down (montmorillonite) than others (quartz). As a result, the coarse-grained soils (sand, gravel) tend to be made of stable minerals such as quartz, whereas the fine-grained soils (silt and clay) tend to be made of less stable minerals such as montmorillonite. Organic soils may contain a significant amount of organic matter (wood, leaves, plants) mixed with the minerals, or may be made entirely of organic matter, such as the peat often found at the edges of swamps. Figure 2.7 shows some of those soils categories. Note that what the geotechnical engineer calls *soil* may be called *rock*

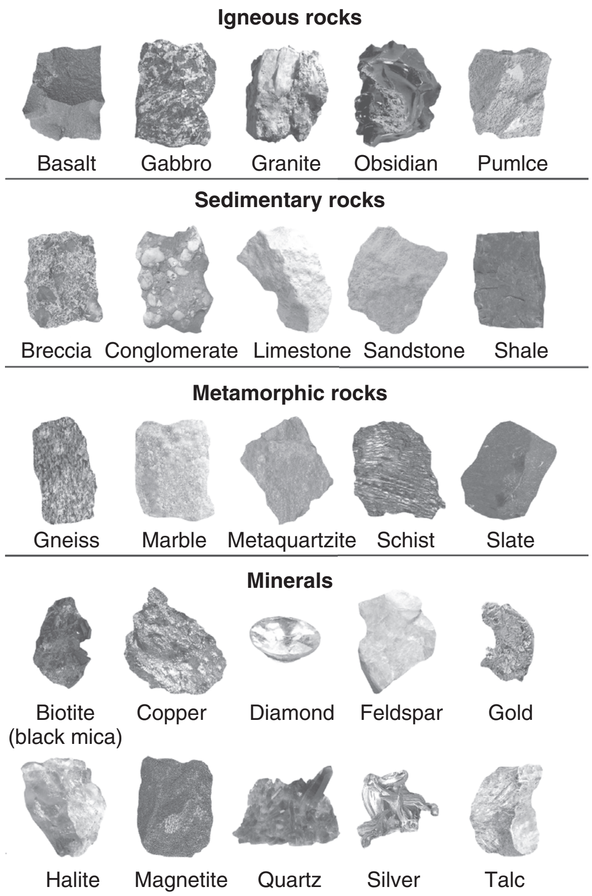

Figure 2.6 Main categories of rocks. (Courtesy of EDUCAT Publishers)

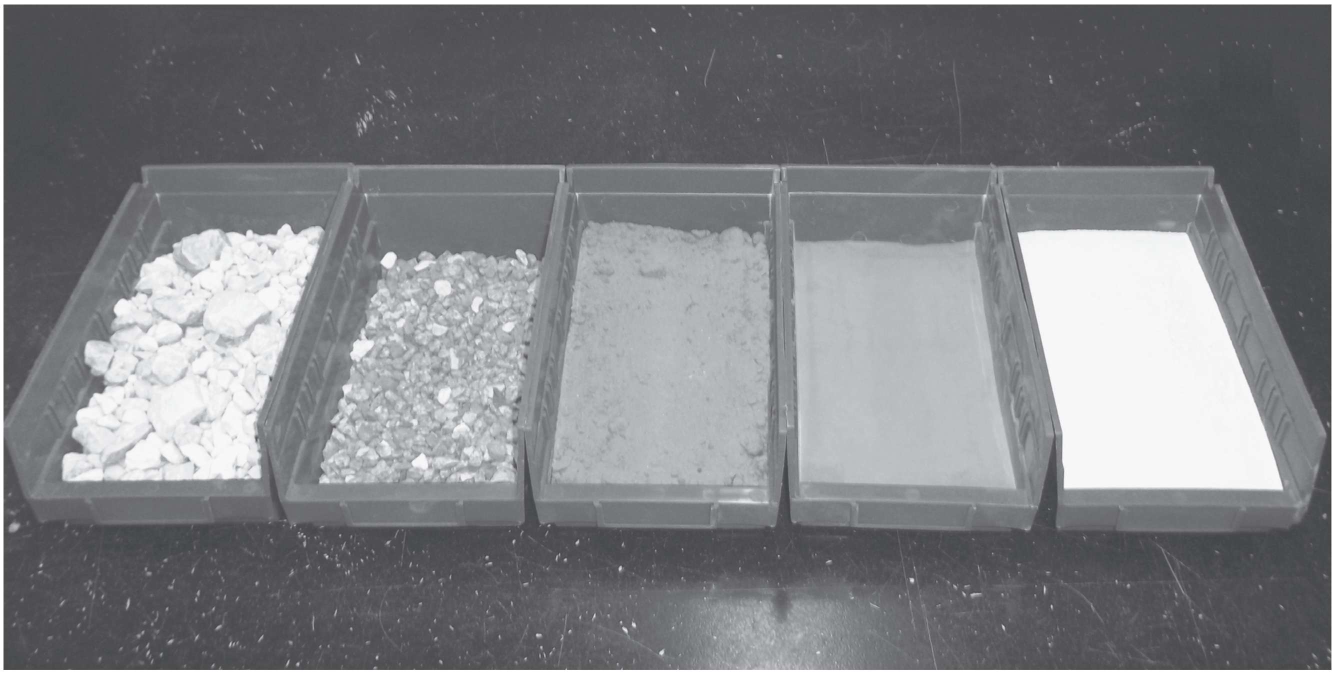

Figure 2.7 Main soil categories (crushed rock, gravel, sand, silt, clay).

by the engineering geologist; this can create confusion during discussion and interpretation.

2.6 GEOLOGIC FEATURES

The ability to recognize geologic features helps one to assess how the material at the site may be distributed. These features (Waltham 1994; Bell 2007) include geologic structures (faults, synclines, anticlines), floodplains and river deposits (alluviums, meander migration), glacial deposits (glacial tills and boulders left behind by a glacier), arid landforms (dunes, collapsible soils, shrink-swell soils), and coastal processes (shoreline erosion, sea-level changes).

The following list identifies some of the most common and important geological features that can affect geotechnical engineering projects.

Faults (Figure 2.8) are fractures in a rock mass that has experienced movement. They can lead to differences in elevation at the ground surface, differential erosion, contrasting visual appearance, and weaker bearing capacity of the fault material compared to the parent rock.

Outcrops show up at the ground surface when the rock layers are inclined. The area on the ground surface associated with an outcrop depends on the thickness of the layer and its *dip* or angle with the horizontal.

Escarpments are asymmetric hills formed when an outcrop is eroded unevenly or when the edge of rock layers is not flat. A *cliff* is an extreme case of an escarpment.

Folds (Figure 2.9) are created when rock layers are curved or bent by earth crust movement. *Synclines* are concave features (valleys), whereas *anticlines* are convex features (hills). Folds are best seen on escarpments.

Inliers and outliers are the result of erosion. Older rocks are typically below younger rocks. When an anticline erodes, the old rock appears at the surface between two zones of younger rocks (inlier). When a syncline erodes, it can lead to the reverse situation (outlier).

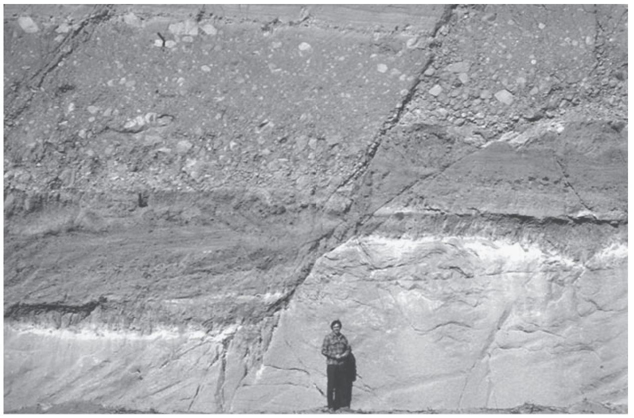

Figure 2.8 Example of rock fault. (Courtesy of USGS U.S. Geological Survey.)

Figure 2.9 Example of anticline–syncline combination. (Photo by R. W. Schlische.)

Figure 2.10 Examples of sinkholes. (*Left*: Courtesy of R.E. Wallace, United States Geological Survey, USA,; *Right*: Courtesy of International Association of Certified Home Inspectors, Inc.)

Karst is the underground landscape created when limestone is eroded or dissolved by groundwater. This process leads to holes in the limestone, called *sinkholes*, which can range from 1 meter to more than 100 meters in size and may become apparent while drilling during the site investigation (Figure 2.10).

Subsidence refers to settlement of the ground surface over large areas (in the order of square kilometers). Subsidence can be caused by pumping water out of the ground for irrigation or drinking purposes (Houston, Mexico City), pumping oil, digging large tunnels and mines, the presence of sinkholes, melting of the permafrost, and wetting of certain soils that collapse in the presence of water (called *collapsible soils*).

Meander migration occurs because rivers are dynamic features that change their contours by lateral erosion, particularly around bends or meanders. The soil forming the bank on the outside of the meander is eroded and is sent to the inside of the meander by the helical current of the river as it takes the meander turn. The inside of the meander then forms a sand bar (Figure 2.11).

Flood plain deposits occur when rivers experience flooding and the water spills over from the main channel into the floodplain. The main channel is a high-energy deposition environment, and only coarse-grained soils heavy enough

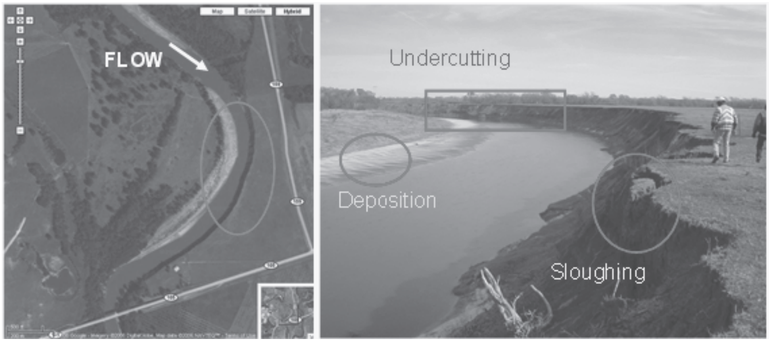

Figure 2.11 Example of meander migration.

not to be transported away are found there. In contrast, floodplains are a low-energy deposition environment where fine-grained soils are typically found. Floodplains and main channels can end up being buried or abandoned as the river migrates laterally and vertically. Abandoned floodplains are called *river terraces*.

Alluvium and *alluvial fans* are soil deposits transported to the bottom of a steep slope by the erosion of a river flowing down that steep slope (Figure 2.12).

Colluvial fans are deposits that form by gravity at the bottom of steep slopes when the slope fails.

Dunes are wind-blown sediments that accumulate over time to form a hill.

Permafrost is a zone of soil that remains frozen year round.

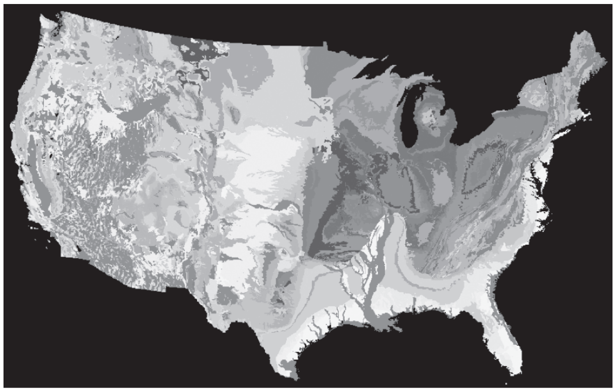

Figure 2.13 Example of geologic map. (Courtesy of National Park Service, NPS.)

2.7 GEOLOGIC MAPS

Geologic maps are very useful to the geotechnical engineer when evaluating the large-scale soil and rock environment to be dealt with in a project. These maps typically have a scale from 1:10,000 to 1:100,000 and show the base rock or geologic unit and major geologic features such as faults. Each rock area of a certain age is given a different color (Figure 2.13); soil is usually not shown on those maps. These maps can provide useful information regarding groundwater and hydrogeology, landslide hazards, sinkhole susceptibility, earthquakes, collapsible soils, flood hazards, and karst topography. Remember that what the geotechnical engineer calls *soil* may be called *rock* by the engineering geologist; to avoid confusion during discussion and interpretation, it is best to clarify the terminology.

Figure 2.12 Example of an alluvial fan. (Courtesy of Mike Norton.)

2.8 GROUNDWATER

Another important contribution of engineering geology to geotechnical engineering is a better understanding of how the groundwater is organized at a large scale. This field involves aquifer conditions, permeability of the rocks, and weather patterns (Winter et al. 1999). If you drill a hole in the ground, at some point you are likely to come to a depth where there is water. This water is called *groundwater* and it comes from infiltration from rain, rivers, springs, and the ocean. It may be stationary or flow slowly underground. If you go very deep (about 3 km or more), you will get to a point where there is no more water and the rocks are dry. The *groundwater table* (Figure 2.14) is the surface of the water within the soil or rock

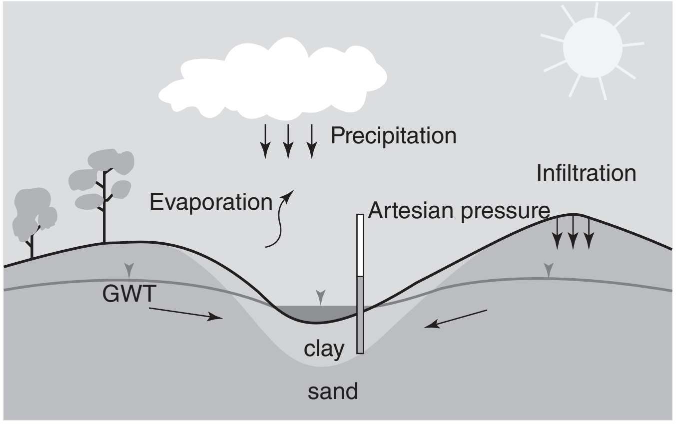

Figure 2.14 Groundwater.

where the water stress is equal to the atmospheric pressure (zero gauge pressure). Under natural conditions and in the common case, the groundwater table is close to being flat.

The *phreatic surface*, also called the *piezometric surface*, is the level to which the water would rise in a tube connected to the point considered in the soil mass. Most of the time, the groundwater table and the phreatic surface are the same. In some cases, though, they are different: *artesian pressure* refers to the case where the pressure in the water at some depth below the groundwater table is higher than the pressure created by a column of water equal in height to the distance between the point considered and the groundwater table. This can occur when a less permeable clay layer lies on top of a more permeable sand layer connected to a higher water source (Figure 2.14). Indeed, if you were to drill a hole through the soil down to a zone with artesian pressure, the water would rise above the level of the ground surface and could gush out into a spring (Figure 2.15).

Figure 2.15 Example of flow due to artesian pressure. (Courtesy of USGS U.S. Geological Survey.)

Perched water is a zone of water in the soil where the water appears at a certain depth in a boring and then disappears at a deeper depth; it acts as a pocket of water in the ground. *Aquifers* are typically deeper reservoirs of water that are supplied by surrounding water through a relatively porous rock. Aquifers are often pumped for human consumption. Their depletion can create kilometers-wide zones of settlement called *subsidence*, and in some instances the settlement can reach several meters in depth.

In geotechnical engineering, it is very important to know where the groundwater table is located, as it often affects many aspects of the project. Furthermore, it is important to identify irregularities in groundwater, such as artesian pressure or perched water.

PROBLEMS

2.1 Calculate the pressure at the center of the Earth.
2.2 Calculate the temperature at the center of the Earth
2.3 What is the depth of interest for most geotechnical engineering projects?
2.4 List the Tertiary and Quaternary epochs.
2.5 What happened about 10,000 years ago on the Earth? What are some of the consequences for soil and rock behavior today?
2.6 What are the three main categories of rocks, and what is the origin of each category?
2.7 What are the four main categories of soil sizes? How were each of these soils generated?
2.8 What engineering geology features can you look for when you visit a site for a geotechnical engineering project?
2.9 How can geologic maps be useful to the geotechnical engineer?
2.10 Define the following terms: groundwater level, perched water, phreatic surface, aquifer.

Problems and Solutions

Problem 2.1

Calculate the pressure at the center of the Earth.

Solution 2.1

To calculate the pressure at the center of the Earth, we will use Newton's law of universal gravitation. The force between two masses, m_1 and m_2, separated by a distance r, is:

$$F = G.\frac{m_1.m_2}{r^2}$$

where G is the gravitational constant $= 6.67 * 10^{-11}$ N m^2 kg^{-2}

The density of soil layers varies with depth; the average density value for each layer is given in the following table:

Layer	Thickness (km)	Average Density (kg/m^3)
Crust	100	2700
Mantle	2800	5000
Core	3500	12000

Consider a small element of Earth dr thick and $rd\theta$ wide at a depth such that the distance from the center of the Earth is r (Figure 2.1s). This small element has a mass dm_1. The force acting on that element consists of three gravitational force components: the force due to mass Ma, which pulls the element away from the center; the force due to mass Mb, which pulls the element toward the center, and the force due to mass Mc, which also pulls the element toward the center. Newton showed that the forces due to mass *Ma* and *Mb* are equal and opposite so that the only force acting on the element is the force due to mass *Mc*. Therefore:

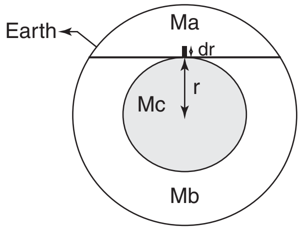

Figure 2.1s Parameters definition.

The pressure P is $P = \frac{F}{A}$ where A is the area of the element, so:

$$dP = \frac{dm_1}{A}.\frac{G.m_2}{r^2} = \frac{\rho.dV}{A}.\frac{G.m_2}{r^2} = \frac{\rho.dr.A}{A}.\frac{G.m_2}{r^2} = \rho.dr.\frac{G.m_2}{r^2}$$

$$P = \int \rho.G.\frac{m_2}{r^2}.dr, \quad \text{where } m_2 = \frac{4}{3}\pi r^3 \rho$$

$$P = \frac{4}{3}\pi.G.\int \rho^2.r.dr$$

Because the density of the Earth's layers is not constant (see Figure 2.2), the pressure at the center of the Earth is:

$$P = \frac{4}{3}\pi \times 6.67 \times 10^{-11}\left(\int_0^{3500\times1000} 12000^2 \text{ rdr} + \int_{3500\times1000}^{6300\times1000} 5000^2 \text{ rdr} + \int_{6300\times1000}^{6400\times1000} 2700^2 \text{ rdr}\right.$$

$$P = 2.79 \times 10^{-4}\left(72r^2\Big|_0^{3.5\times10^6} + 12.5r^2\Big|_{3.5\times10^6}^{6.3\times10^6} + 3.645r^2\Big|_{3.3\times10^6}^{6.4\times10^6}\right) = 3.44 \times 10^{11}\frac{\text{N}}{\text{m}^2} = 344 \text{ GPa}$$

Note that in geotechnical engineering we calculate the pressure, also called *vertical total stress*, at a given depth z as:

$$P = \sum \gamma_i \Delta Z_i$$

Where γ_i is the unit weight of the ΔZ_i thick i^{th} layer within the depth z. This is an approximation, as the unit weight $\text{Y} = \rho$g is not constant and depends on the depth z (since g is a function of z). This approximation is very acceptable for the usual depth involved in a geotechnical project (a few hundred meters at most); indeed, this approximation only makes a difference of a small fraction of a percent.

Problem 2.2

Calculate the temperature at the center of the Earth.

Solution 2.2

The temperature gradient is 15° Celsius per kilometer in the crust and 0.63° Celsius per kilometer in the mantle and the core. Therefore, the temperature at the center of the Earth is:

$$T_{center} = 15 \times 100 + 0.63 \times 6300 = 5469^\circ$$

Problem 2.3

What is the depth of interest for most geotechnical engineering projects?

Solution 2.3

The depth of interest for most geotechnical engineers is a few hundred meters.

Problem 2.4

List the Tertiary and Quaternary epochs.

Solution 2.4

Holocene	0 to 10,000 years ago
Pleistocene	10,000 to 1.8 million years ago
Pliocene	1.8 to 5.3 million years ago
Miocene	5.3 to 23.8 million years ago
Oligocene	23.8 to 33.7 million years ago
Eocene	33.7 to 54.8 million years ago
Paleocene	54.8 to 65 million years ago

Problem 2.5

What happened about 10,000 years ago on the Earth? What are some of the consequences for soil and rock behavior today?

Solution 2.5

An ice age occurred about 10,000 years ago, at the beginning of the Holocene period. At that time, glaciers about 100 meters thick covered the earth from the North Pole down to about the 40th parallel and loaded the soil. This very heavy loading increased the density, stiffness, and strength of the soils below the glaciers. When the glaciers melted, they left behind these very dense, overconsolidated soils, called *glacial tills*. These soils do not settle much as long as the pressure does not exceed the pressure exerted by the Ice-Age glacier. (The glaciers also carried within them very large and heavy rocks, and deposited these boulders along their paths when they melted.) When the glaciers melted, the soil surface rebounded, and in some places this movement still goes on today at a rate of about 10 mm per year. An example of this is the landmass in England.

Problem 2.6

What are the three main categories of rocks, and what is the origin of each category?

Solution 2.6

The three main categories of rocks are:

- Igneous rocks, which come from the solidification and crystallization of magma. Common igneous rocks are granite, basalt, and gneiss.
- Sedimentary rocks, which are composed of rocks previously eroded through wind and hydraulic erosion and recemented by long-term high pressure or chemical agents (e.g., calcium). Common sedimentary rocks are sandstone, limestone, and clay shales.
- Metamorphic rocks, which have been altered by heat and/or pressure. Common types of metamorphic rocks are schist and slate.

Problem 2.7

What are the four main categories of soil sizes? How were each of these soils generated?

Solution 2.7

Soil class	Soil type	Size (by USCS)
Coarse-grained soil	Gravel	75 mm to 4.75 mm
	Sand	4.75 mm to 0.075 mm
Fine-grained soil	Silt	0.075 mm to 2 μm
	Clay	<2 μm

Soils are generated by the exposure of rocks to the weather and other altering mechanisms. The weathering can be physical (wetting/drying, thermal expansion, frost shatter) or chemical (solution, oxidation, and hydrolysis). Erosion and deposition is another mechanism responsible for soil formation.

Problem 2.8

What engineering geology features can you look for when you visit a site for a geotechnical engineering project?

Solution 2.8

- Geologic structures (faults, synclines, anticlines)
- Floodplains and river deposits (alluviums, meander migration)
- Glacial deposits (glacial tills and boulders left behind after glacier melting)
- Arid landforms (dunes, collapsible soils, shrink-swell soils)
- Coastal processes (shoreline erosion, sea level changes)

Problem 2.9

How can geologic maps be useful to the geotechnical engineer?

Solution 2.9

Geologic maps help geotechnical engineers to evaluate the soil and rock in an area and to find specific geologic features such as faults.

Problem 2.10

Define the following terms: groundwater level, perched water, phreatic surface, aquifer.

Solution 2.10

Groundwater level: the level at which water is found in an open borehole.

Perched water: a zone of water in the soil where the water appears at a certain depth in a boring and then disappears at a deeper depth; it acts as a pocket of water in the ground.

Phreatic surface: the level where the water would rise in a tube connected to the point considered in the soil mass. Most of the time, the groundwater table and the phreatic surface are the same. Some exceptions include artesian pressure and water flow.

Aquifer: a deep reservoir of water created by infiltration of surrounding water through a porous soil or rock. Drinking water may come from an aquifer.