

CHAPTER 1

SOIL FORMATION, COMPOSITION, AND BASIC CONCEPTS

1.1 WEATHERING PROCESSES, SEDIMENTARY AND RESIDUAL SOILS

The word *soil* is used in soil mechanics to mean any naturally formed mineral material that is not rock. It thus covers all loose material ranging in particle size from clay through silt and sand to gravel and boulders. The main focus of soil mechanics is the material at the fine end of the range, particularly clay and silt and to a lesser extent sand.

Soils are formed by the physical and chemical weathering of rock. **Physical weathering** may be one of two types. First, there is disintegration—caused primarily by wetting and drying or by freezing and thawing in cracks in the rock. Second, there is erosion—caused by the action of glaciers, water, or even wind. These processes produce a range of particles of varying sizes which are still composed of the same material as the parent rock. Sand and silt particles produced by physical weathering generally consist of single rock minerals, rather than combinations of these, as is the case in their parent rock or in gravel-sized material. It is important to recognize that no matter how fine the particle size of the material produced by physical weathering may be, it can never have the properties of clay because the chemical conversion needed to form true clay particles is not present.

Chemical weathering processes are much more complex and involve chemical changes to the mineral content of the parent rock caused by the action of percolating water, oxygen, and carbon dioxide. The minerals of which rock is composed are converted into a very different group of

materials known as clay minerals. Well-known members of this group are kaolinite, illite, and montmorillonite, but less well known clay minerals of considerable importance in volcanic areas are halloysite and allophane. Clay mineral particles are generally crystalline in form and are of colloidal size, that is, they are less than 0.002 mm. These minerals give soil the properties of cohesion and plasticity, which are the distinctive characteristics of clay.

The nature of the clay mineral produced in any given situation is dependent on both the parent rock and the weathering environment, in particular the local climate, whether the site is well drained, and whether the percolating water is acidic or alkaline. For example, kaolinite is formed from feldspar by the action of water and carbon dioxide. Quartz is one of the minerals most resistant to weathering, so that soils weathered from granite tend to have a substantial proportion of coarse quartz particles within a matrix of finer material. Weathering is most intense in warm, wet climates and least intense in cold, dry climates. In the wet tropics, weathering can extend to many tens of meters below the ground surface. The chemical processes involved in weathering are complex and not of direct interest or concern to geotechnical engineers; it is the properties of the end product that are of paramount interest.

Apart from the direct physical and chemical processes that convert rock to soil, there are other processes that transport soil particles and redeposit them in lakes and the ocean. This process is illustrated in Figure 1.1. The soil formed directly from the chemical weathering process is called a **residual soil**. It remains in place directly above and in contact with its parent rock. Rainfall erodes some of this residual soil and transports it via streams and

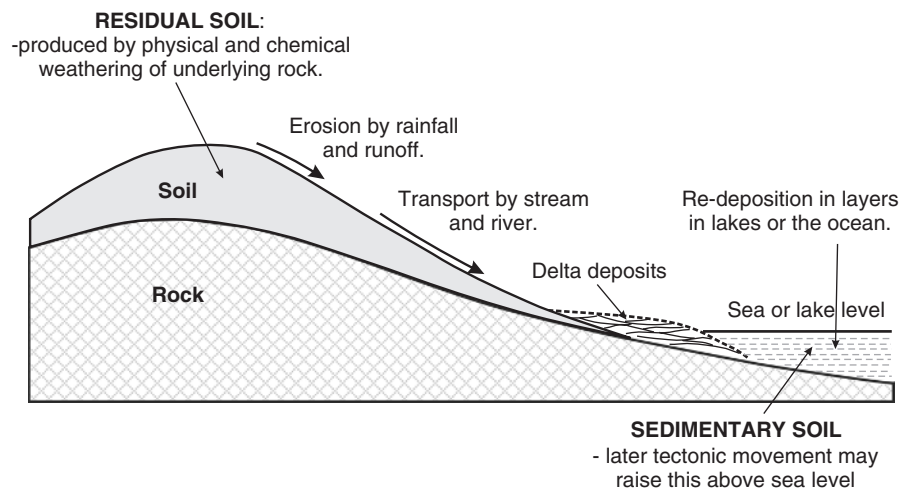


Figure 1.1 Soil formation processes.

rivers to eventually end up in lakes or the sea where it is redeposited as sediment at the bottom of the lake or sea. This process may continue for many thousands or millions of years, and the soils undergo a great deal of compression, or “consolidation,” as additional layers are deposited above them. In this way the soil can build up to a great thickness. Soils formed in this way are termed **sedimentary soils** or **transported soils**.

Once formed, sedimentary soils undergo further changes due to the weight of overburden material above them as well as natural hardening, or “aging,” processes. Seeping water influences these processes, possibly by providing chemical cementing agents that tend to bond the soil particles together or by dissolving some materials or chemicals present in the soil, a process known as leaching. In many situations, compression from the weight of overlying material combined with chemical cementing processes converts the soil into a sedimentary rock. Sandstones and clay stones (or mudstones) are formed in this way.

These sedimentary soils may be uplifted later by tectonic movement, so that in many parts of the world today they exist far from the sea or lake where they were formed and well above sea level. Once they are uplifted in this way, the erosion cycle from rain and streams begins all over again, and the thickness of the soil decreases.

1.2 CLAY MINERALS

Clay minerals are a very distinctive type of particle that give particular characteristics to the soils in which they occur. The most well known clay minerals are kaolinite, illite, and montmorillonite. These have a crystalline structure, the basic units of which are termed a silica tetrahedron and an alumina octahedron. These units combine to form sheet structures, which are usually represented graphically in the form shown in Figure 1.2. The actual clay mineral particles are formed by combinations of these basic sheets, which form multilayered “stacks,” as indicated in Figure 1.2. The nature of the bonds between the sheets has a very important influence on the properties of the whole particle.

Kaolinite particles have a basic structure consisting of a single sheet of silica tetrahedrons and a single sheet of alumina octahedrons. These combined sheets are then held in a stack fairly tightly by hydrogen bonding. Illite particles have a basic structure made up of a central alumina sheet combined with silica sheets above and below. The combined sheets are in turn linked together by potassium ions sandwiched between them. This is a fairly weak form of bond. Montmorillonite is made up of the same basic unit as illite, but the form of bond between these basic units is different. Water and exchangeable cations provide this bond, which is a much weaker bond than that in illite particles.

This special structure means that these clay particles are not inert, as are rock particles. The term “active” is used to describe clay minerals, meaning

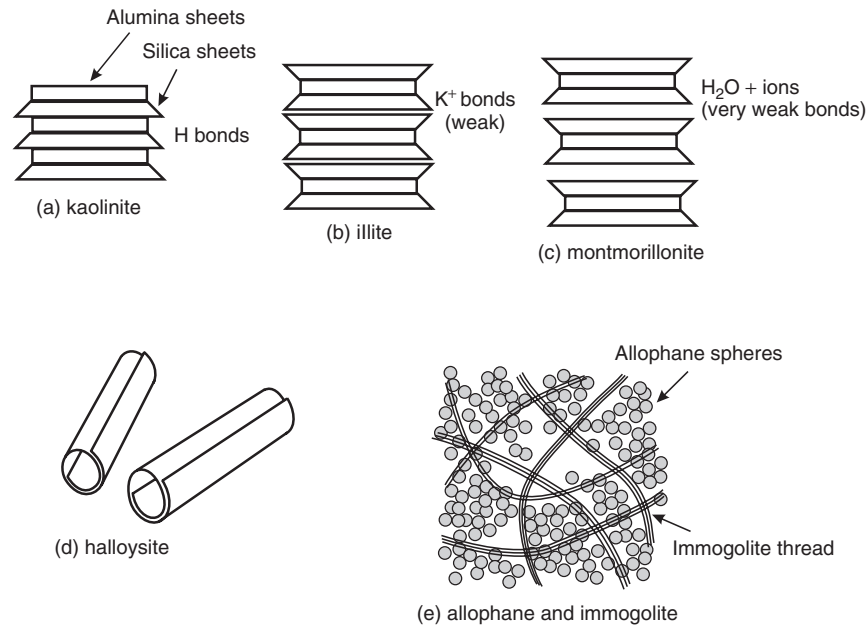


Figure 1.2 Schematic of clay minerals.

they are capable of swelling and shrinking by taking in water or losing it, depending on the environment surrounding them. Kaolinite is of relatively low activity, illite of medium activity, and montmorillonite of high activity. In general, the higher the activity of the clay, the less favorable the engineering properties of the soil. Montmorillonite clays are of relatively low strength as well as being highly compressible and often cause problems with foundations because of shrinkage or swelling. On the other hand, kaolinite clays, because of their low activity, have relatively good engineering properties. We can note that there are some engineering situations where high activity is desirable, as, for example, in some water-retaining structures where a low-permeability, highly plastic material is required as a barrier to seepage.

In addition to these common clay minerals, there are two rather unusual minerals often found in clays derived from the weathering of volcanic material. These are halloysite and allophane/immogolite. Although distinct, allophane and immogolite normally occur together. These minerals are formed from the weathering of volcanic “ash,” a loose silt- or sand-sized material produced by volcanic eruptions, especially andesitic eruptions. Unlike rocks and other volcanic material such as coarse pyroclastic deposits (material produced by explosive events) and lava flows, volcanic ash particles do not have a crystalline structure and for this reason undergo a different and unique weathering process that leads to the formation of halloysite

and allophane. The form of these materials is illustrated diagrammatically in Figure 1.2. Both are of much smaller particle size than the three well-known clay minerals already described and have a less well developed crystalline structure. The allophane and immogolite diagram is based on an electron micrograph of Wada (1989). A detailed account of the geotechnical properties of allophane clays is given by Wesley (2002).

Halloysite consists of cylindrical “rolls” some of which are properly formed and others are mere fragments. Allophane and immogolite normally occur together; the allophane particles are essentially spherical in shape, while immogolite has the form of long threads that weave between the allophane spheres. While the well-known clay minerals kaolinite, illite, and montmorillonite consist of particles somewhat less than 0.002 mm (2 μm) in size, the spherical allophane particles are approximately one thousand times smaller. Neither halloysite nor allophane/immogolite is of high activity. Allophane/immogolite soils are very unusual, being characterized by extremely high water contents and Atterberg limits (described in chapter 3). Despite this they have remarkably good engineering characteristics.

Current understanding of the weathering of volcanic ash is that it involves the following sequence, at least in wet tropical areas where the weathering process is intense:

Ash \longrightarrow allophane/immogolite \longrightarrow halloysite \longrightarrow kaolinite \longrightarrow sesqui-oxides \longrightarrow laterite

The progress of weathering from kaolinite to sesqui-oxides involves the leaching out of the silica-based minerals and the concentration of aluminum and iron compounds known as sesqui-oxides. With time, these compounds act as cementing agents, forming “concretions,” and the material becomes a nonplastic, sandy gravel. This material is known as laterite, and the weathering process that produces it is termed laterization. This laterization process can occur in both volcanic and nonvolcanic soils, although it appears to be more common in the former. In cooler climates, the weathering may not progress as far as the formation of laterite.

1.3 INFLUENCE OF TOPOGRAPHY ON WEATHERING PROCESSES

Topography has a strong influence on the weathering process and thus on the type of soil formed (see Figure 1.3). This is especially true in the wet tropics. In hilly and mountainous areas, the soil is well drained with seepage tending to occur vertically downward. This leads to the formation of low-activity minerals, especially kaolinite. In volcanic areas, the minerals allophane and halloysite are likely to be formed initially, leading with time to the formation of kaolinite, as noted above. Soils containing these minerals generally have good engineering properties.

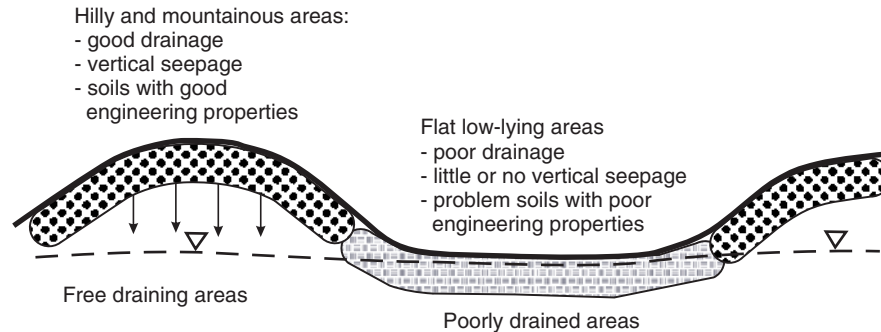


Figure 1.3 Influence of topography on clay mineral formation.

In wide, flat, areas, drainage of any sort is much more limited, and the weathering process is quite different. It tends to produce montmorillonite and associated highly active minerals. This is particularly the case in wet tropical areas that have distinct wet and dry seasons. Clays of this sort are called vertisols by soil scientists because the cyclic wetting and drying process and associated surface cracking tend to cause movement of water (and soil) in both the upward and downward direction close to the surface. These soils are often termed black clays by geotechnical engineers and generally have poor or undesirable engineering properties.

1.4 FACTORS GOVERNING THE PROPERTIES OF SEDIMENTARY AND RESIDUAL SOILS

The title of this book possibly suggests that sedimentary and residual soils are quite distinct materials with different mechanical or physical properties. There is important, but limited, truth to this suggestion. Many of the fundamental principles that govern soil behavior, in particular the principle of effective stress (Chapter 4), the laws governing seepage (Chapter 7), and the Mohr–Coulomb shear strength failure criterion (Chapter 9), are equally applicable to both groups. The stability concepts governing foundation design, earth pressure, and slope stability (Chapters 11–14) are also of universal applicability. However, there are some aspects of residual and sedimentary soil behavior that are different and can only be appreciated if we have a sound understanding of the processes by which these two soil groups are formed. At the risk of being repetitive, we will therefore give further consideration to the formation process of the two groups and the influence this has on their properties.

Residual soils are the direct product of the weathering of their parent rock and are generally more closely related to characteristics of their parent rock than is the case with sedimentary soils. They often exhibit a property known as “structure”; that is, the particles are packed together or

even bonded together in a way that forms a soil “skeleton” having characteristics quite different from those of a simple collection of individual particles.

Sedimentary soils undergo various additional processes beyond the initial physical and chemical weathering of the parent rock and subsequent transport and redeposition. In particular, they undergo compression from the weight of the layers deposited above them, making them stronger or harder. In some situations the load on the soil may later be reduced as a result of subsequent geological uplift and erosion processes. Soils that have not been subjected to stresses greater than those currently acting on them are termed **normally consolidated** soils, while those that have had higher loads on them sometime in the past are called **overconsolidated** soils. The sequence of stresses to which the soil has been subjected since its formation is termed its **stress history**. Figure 1.4 is an attempt to illustrate the processes involved in the formation of the two groups.

While stress history has been an important concept (for sedimentary soils) in soil mechanics since its inception, it has been increasingly recognized that other factors, especially the cementation and hardening effects that occur with time (aging), are equally important. This means that structure may be just as important in sedimentary soils as in residual soils and is becoming an increasingly important focus of research.

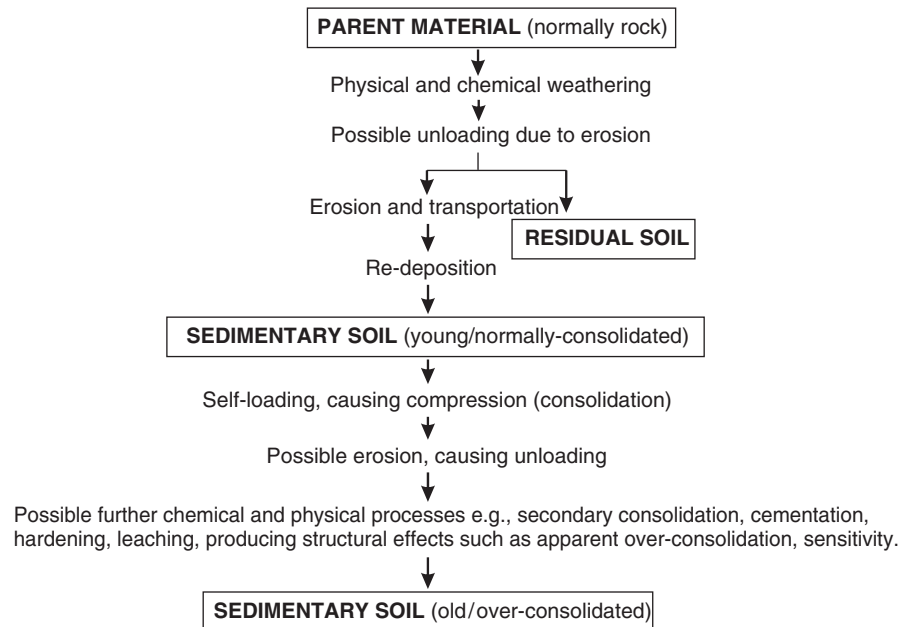


Figure 1.4 Formation factors influencing properties of sedimentary and residual soils.

The formation of both soils is complex, but two important factors lead to a degree of uniformity and predictability with sedimentary soils that is absent from residual soils:

- (a) The sorting processes that take place during erosion, transportation, and deposition of sedimentary soils tend to produce homogeneous deposits. Coarse particles get deposited in one place and finer particles in a different place.
- (b) Stress history is a prominent factor in determining the behavioral characteristics of sedimentary soils and leads to a convenient division of these soils into normally consolidated and overconsolidated materials.

The absence of these two factors with residual soils means that they are generally more complex and less capable of being divided into tidy categories or groups.

It is worth noting at this point that with time the processes forming these two soil groups tend to have an opposite effect on their properties, as illustrated in Figure 1.5. The weathering of rock tends to make the rock less dense and steadily reduces its strength. Solid rock contains essentially no void space whereas soils often contain a similar or greater volume of voids than solid particles. With some soils, solid material makes up as little as 20 percent of the volume of the soil. The term “void ratio” is used to define the volume of void space in a soil and is the ratio of the volume of voids to the volume of solid material (i.e., the soil particles).

With sedimentary soils, the compression of the soil from the weight of material above it together with the aging effect makes it denser and harder. Figure 1.5b shows a graph illustrating the way the void space in the soil steadily decreases as the weight of material above it increases. If the load on it is reduced, which could occur as a result of tectonic uplift followed by erosion, there will be some “rebound” of the soil with a small increase in void content, as shown in the figure.

We can summarize the principal aspects of residual soils that distinguish them from sedimentary soils as follows:

1. Residual soils are often much more heterogeneous (nonuniform) than sedimentary soils. Despite this, there are some residual soils that are just as homogeneous as typical sedimentary soils. Tropical red clays are often in this category.
2. Some residual soils, especially those of volcanic origin, may contain very distinctive clay minerals not found in sedimentary soils and which strongly influence their behavior.

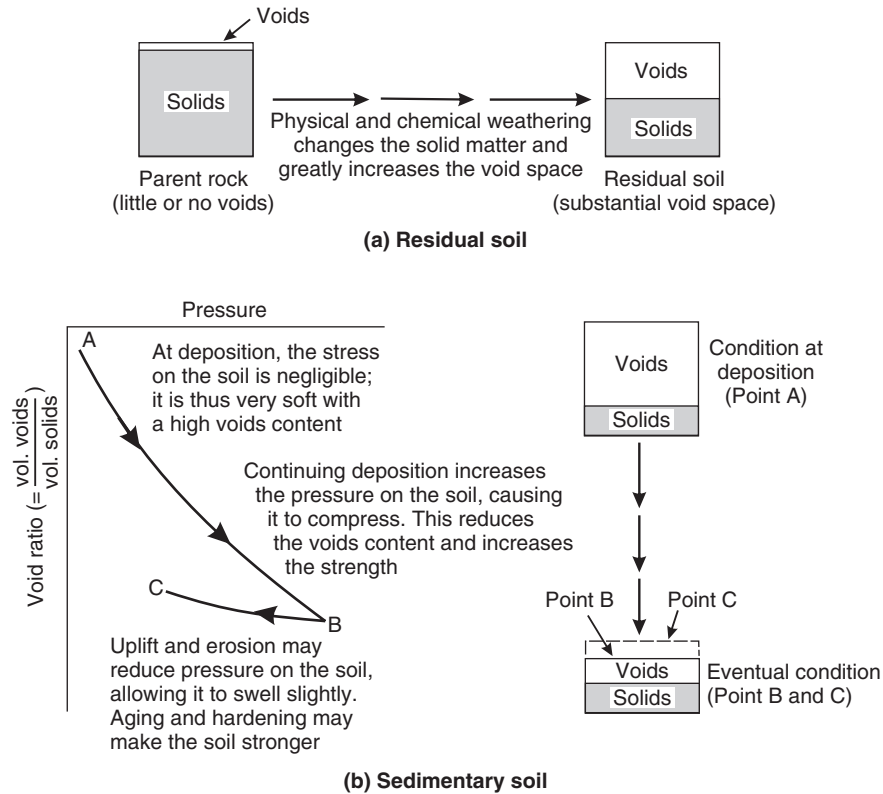


Figure 1.5 Formation processes and density of residual and sedimentary soils.

3. Some residual soils are not strictly particulate, that is, they do not consist of discrete particles. They may appear to consist of individual particles, but when disturbed or subjected to shear stress, these particles disintegrate and form an array of much smaller particles.
4. Stress history is not a significant formative influence on the properties of residual soils.
5. Some behavioral frameworks based on the study of sedimentary soils, especially the logarithmic plot used to express compressibility (Chapter 8), may not be helpful to an understanding of the behavior of residual soils.
6. Empirical correlations between soil properties developed from the study of sedimentary soils may not be valid when applied to residual soils.

7. The pore pressure state above the water table (Chapter 4) is of considerably more relevance to understanding the behavior of residual soils than is the case with sedimentary soils. Much of the action of immediate concern to geotechnical engineers takes place above the water table rather than below it.

The discipline soil mechanics developed in northern Europe and North America, and its basic concepts evolved from the study of sedimentary soils, which are the dominant soil type in these areas. It is perhaps not surprising therefore that few textbooks or university courses on soil mechanics even mention residual soils, let alone give an adequate account of their properties. This might be appropriate if all soils were sedimentary soils. This is not the case; probably more than half the earth's surface consists of residual soils. For this reason, this book attempts to give equal coverage to both residual and sedimentary soils.

1.5 REMOLDED, OR DESTRUCTURED, SOILS

In addition to these two groups of natural soils, there is a third group of soils that are no longer natural and are therefore of much less importance to geotechnical engineers. These are soils that have been disturbed and/or remolded so that they no longer retain important characteristics of their undisturbed in situ state. This group includes soils prepared by sedimentation from an artificial slurry, which are often used to investigate sedimentary soil behavior, and also compacted soils.

The term **destructured** is frequently used these days to designate these soils and has a slightly different meaning from the term **remolded**. The term "destructured" means that the soil has been manipulated in such a way that bonds between particles or any other structural effects are destroyed, but the particles themselves are not altered. "Remolding" is a somewhat vague term but is generally taken to mean that the soil has been thoroughly manipulated, and any special characteristics associated with its undisturbed state are no longer present. With residual soils, thorough remolding may well completely destroy some particles as well as destroy the structure of the material.

The properties of remolded soils are thus not governed by any form of structure, as is normally the case with most undisturbed soils, regardless of whether they are residual or sedimentary. Compacted clays may be an exception to this statement to a small extent, as it is possible that the compaction process does create some form of structure. For example, compacted clays tend to have a higher permeability in the horizontal direction than in the vertical direction, due to the horizontal layering effect produced by the compaction method. They may also have a greater stiffness in the vertical direction than the horizontal direction.

REFERENCES

- Wada, K. 1989. Allophane and imogolite. In J. B. Dixon and S. B. Weed (eds.), *Minerals in Soil Environments* (2nd ed.). SSSA Book Series No 1., pp. 1051–1087. Madison, WI: Soil Science Society of America.
- Wesley, L. D. 2003. Geotechnical characterization and behaviour of allophane clays. In *Proc. International Workshop on Characterisation and Engineering Properties of Natural Soils*, Vol. 2, Singapore, December 2002. Leiden: A. A. Balkema, pp. 1379–1399.

