

CHAPTER 1

FUNDAMENTAL ASPECTS OF RESIDUAL SOIL BEHAVIOR

1.1 INTRODUCTION

My main objective in writing this book is to provide geotechnical engineers with some basic guidelines that may be helpful to them when working in residual soils. I hope it will be especially useful to those encountering residual soils for the first time. The book should also be of value to students wishing to further their basic understanding of residual soil behavior. It is not my intention to give detailed descriptions of the many types of residual soils found on the planet, and thus provide a sort of handbook that engineers could refer to when encountering any particular residual soil type. Rather I will try to identify and explain the basic aspects of soil behavior that are specific to residual soils, and that geotechnical engineers working in residual soils should be aware of. There is one exception to the omission of detailed descriptions of specific residual soil types, and that is volcanic soils. These have the most distinctive and highly unusual properties, and are a soil group in which the author has particular experience. For these reasons, one whole chapter (Chapter 9) is devoted to these soils.

The extent to which residual soils differ from sedimentary soils is a matter of some debate. On the one hand, it can be argued that the most basic principles of soil mechanics are equally applicable to both residual and sedimentary soils. In particular, the principle of effective stress and the Mohr-Coulomb failure criteria are of universal applicability. On the other hand, it can be argued that fundamental differences in the way the soils

are formed mean that residual soils are a “class apart” and must be treated differently. For example, Vaughan (1985) states:

The development of the “classical” concepts of soil mechanics (in which soil properties are related and classified according to index properties, plasticity, stress history and the like) has been based almost exclusively on the investigation of sedimentary deposits of un-weathered soil. These concepts have been found almost universally inapplicable to the behaviour of residual soils, and misleading if inadvertently applied.

There is considerable truth in both of the above positions, as should become apparent from the material presented in this book. The first and most important point to appreciate is that there is indeed a fundamental difference in the way residual and sedimentary soils are formed and, at the risk of tedious repetition of material that most readers may already be familiar with, I will consider formation processes in some detail in the next section.

I should mention at this point that my experience in geotechnical engineering in residual soils is largely limited to the wet tropics of Southeast Asia, in particular, Malaysia and Indonesia, and the temperate climate of New Zealand. The contents of this book are thus strongly influenced by the soil conditions in these countries, which are predominately moderate to high plasticity clays. This fact, along with the wet climate, means that the soils are generally fully saturated, or sufficiently close to full saturation that for practical engineering purposes they can be assumed to be so. In this environment, only a shallow zone at the surface is likely to experience partial saturation, caused by evaporation during dry weather, and not because water drains out of the soil under the influence of gravity. This book, therefore, is primarily about fully saturated clays of moderate to high plasticity.

1.2 FORMATION PROCESSES AND BASIC DIFFERENCE BETWEEN RESIDUAL AND SEDIMENTARY SOILS

The basic processes by which soils are formed are illustrated in simplified form in Figure 1.1. Residual soils are formed directly by the physical and chemical weathering of the rock underlying them. Sedimentary soils undergo additional processes; the residual soil is eroded by rainfall and then transported by streams and rivers to be deposited in lakes or the sea as indicated in Figure 1.1. The soil thickness steadily grows as deposition continues; at the same time, it undergoes consolidation from its self-weight. With time, the soil may experience uplift as a result of tectonic movement and end up on dry land, where the erosion cycle will start all over again.

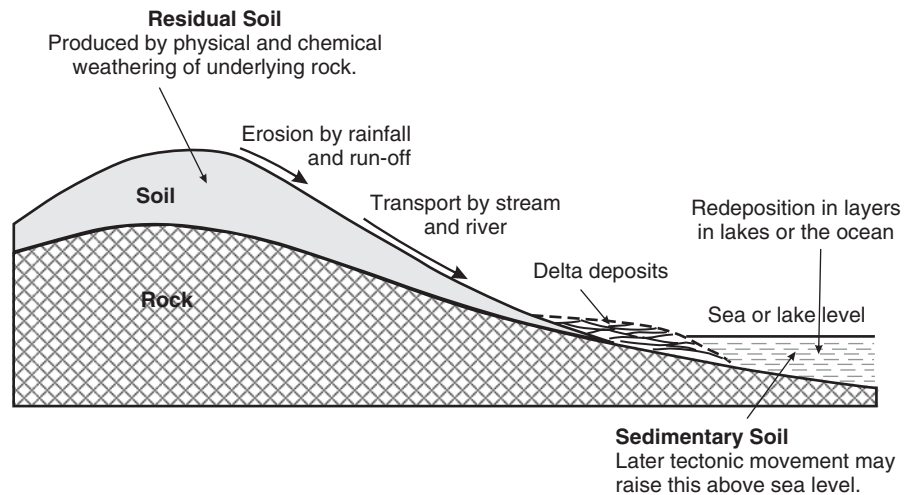


Figure 1.1 Formation of sedimentary and residual soils.

Figure 1.2 is a further attempt to illustrate the fundamental difference in the way the two soil groups are formed, and to help identify the factors that govern their properties. The formation process tends to influence their properties in an opposite manner. With residual soils, the weathering process normally converts solid rock into small particles and clay minerals, inevitably making the material less dense and weaker. With sedimentary soils, the compression of the soil from the weight of material above it, together with aging effects (to be described in the next section) makes it denser and harder.

Two significant differences between residual and sedimentary soils become apparent from the above account of their formation:

1. Sedimentary soils undergo a systematic sorting process during erosion, transportation, and deposition. Finer particles are separated from coarse particles and are deposited in different locations or layers. Sedimentary soils, therefore, tend to be reasonably homogeneous. Residual soils do not undergo these processes, and are likely to be much more heterogeneous than sedimentary soils.
2. The concepts of stress history, normal consolidation, and overconsolidation have no relevance to residual soils. There is no such thing as the virgin consolidation line of a residual soil, a fact that is not always appreciated by those investigating their properties. The “virginal state” of a residual soil is the parent rock from which it is formed, not a soft sediment at the bottom of the sea or a lake (as is the case with sedimentary soils).

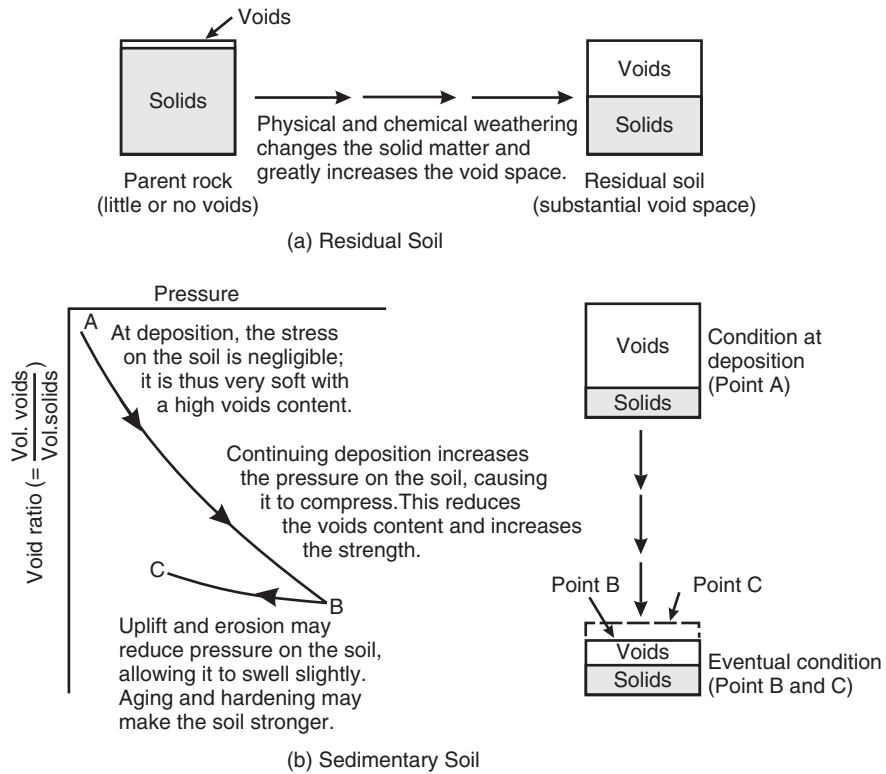


Figure 1.2 Another portrayal of the formation of residual and sedimentary soils.

The above factors mean there is a degree of homogeneity and predictability with sedimentary soils that is absent from residual soils. The convenient behavioral framework whereby the properties of sedimentary soils are related to stress history and divided into normally consolidated and overconsolidated soils cannot be applied to residual soils. Readers may find it helpful to think of residual soils as a raw, unkempt, and unpredictable group, which (though not generally ill behaved) lack the tidy, refined behavior of sedimentary soils, which have been through a proper “finishing” school.

These differences between the two soil groups are elementary and accepted by the geotechnical fraternity, at least to the extent that residual soils are regarded as a separate group and given special treatment in the form of conferences, symposia, and books devoted specifically to them. However, despite this recognition as being different from sedimentary soils, residual soils still tend to be investigated and evaluated as though they are sedimentary soils. In this respect there is a good deal of truth in the statement of Vaughan quoted above. The most striking example of

this is the continuing interpretation of standard oedometer tests using a framework developed from sedimentary soils. Graphs are plotted using the e -log p format and are routinely interpreted wrongly in terms of a *preconsolidation* pressure separating a virgin consolidation line from an unloading–reloading line. This issue is described in some detail in the author’s earlier book (Wesley 2009) and is discussed in further detail in Chapter 4 of the present book.

1.3 STRUCTURE OF RESIDUAL SOILS

The term *structure* is widely used in soil mechanics, although not always with the same meaning. In the early days of the subject it appears to have been used mainly to describe those features of the soil that are clearly visible to the naked eye, such as bedding planes, joints, fault discontinuities, and root holes. These features are best termed *macrostructure*. In more recent times structure has been used more specifically to designate the way in which the particles are arranged to form the soil skeleton itself. A highly structured soil is one in which the particles are arranged or even bonded together in such a way that the soil skeleton has characteristics quite different from those of a simple collection of individual particles. This kind of structure cannot be seen with the naked eye, and is termed *microstructure*. The term will be used in this book primarily to designate *microstructure*.

The existence of microstructure in soils has long been recognized, in both sedimentary and residual soils; indeed, it is evident from the fact that nearly all natural soils have some sensitivity. At the same time, its importance in influencing soil behavior seems to have been rather lost sight of, or displaced, in favor of the stress history model of soil behavior. In recent years, however, the influence of structure has been increasingly recognized, in both sedimentary and residual soils. It is recognized, for example, that very few soft sedimentary clays that are “normally consolidated” geologically actually behave as normally consolidated soil. They behave as lightly overconsolidated clays due to a steady increase in strength with time after their deposition. The terms *aging* or *hardening* are being increasingly used to describe this effect. It is recognized also that structure may play a significant role even in the behavior of stiff sedimentary clays. For example, Gasparre et al. (2007) give an account of the influence of structure on London clay.

Many residual soils, but certainly not all, are highly microstructured, and various conceptual pictures of their structure have been put forward. Several examples are shown in Figure 1.3. The first diagram, Figure 1.3a, for a “normal” undisturbed clay, shows an array of plate-like clay particles occupying void space between the coarser silt or fine sand particles. Soils with such an arrangement of particles may be relatively insensitive, indicating

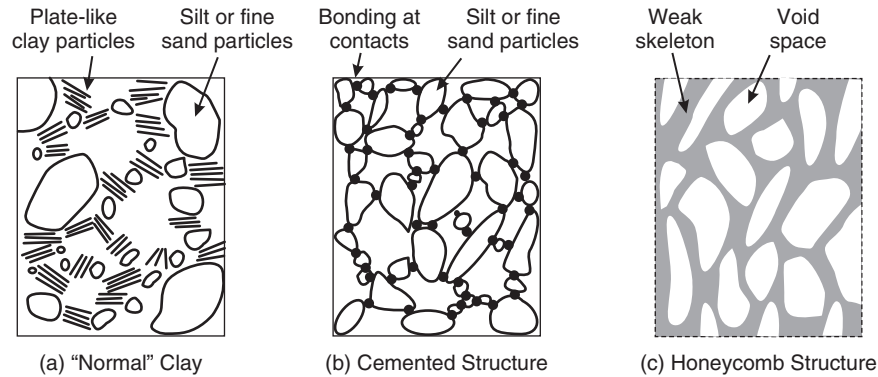


Figure 1.3 Conceptual pictures of soil microstructure.

that the influence of structure is not great, or they may be highly sensitive, as in the case of “quick” clays, indicating that they are highly structured.

Figure 1.3b shows a common concept of the structure of cemented or bonded soils, particularly residual soils. This is a useful concept, and artificially bonded soils have been created and used in laboratory studies of soil behavior, in the belief that this is a reasonable representation of residual soil behavior. Examples are Maccarini (1987) and Toll et al. (2006). These are valuable studies, but we should note their limitations, especially with respect to residual soils. The weathering process, at least in igneous rocks and other hard rocks, is normally one that weakens the rock by breaking it up and converting rock minerals into clay minerals, not one that cements together existing hard particles. Thus, the first concept above, Figure 1.3a, may be just as valid for some residual soils as Figure 1.3b. Some particular weathering processes may still produce the cemented structure of Figure 1.3b.

Finally, Figure 1.3c shows a honeycomb structure, which consists of a skeleton of relatively weak material with very large void space. The honeycomb material may be a single material or may be concentrations or aggregations of particles. This honeycomb structure appears to be valid for many sensitive or highly sensitive volcanic soils. We shall see later that the weathering of siltstones or mudstones (shales) may be different again from the above concepts, and may involve the solution of bonding material and the release of preexisting clay minerals, rather than the creation of new clay minerals or bonds between particles.

The concepts illustrated in Figure 1.3 are likely to be gross oversimplifications of the true situation. They are included here to give the reader an indication of how soil structure can be visualized. The most essential point to be appreciated with respect to soil structure is that compression of the soil does not just involve pressing the particles into a tighter arrangement.

It also involves destroying the natural structure of the soil, and in effect producing a new material. Compression of structured soils is thus also a form of remolding the soil. The point at which the structure begins to collapse may indicate a yield pressure in the soil but this is not necessarily the case. The influence of soil structure on the compression behavior of residual soils is discussed further in Chapter 4. For an interesting and detailed description of the structure of one particular soil see Zhang et al. (2007).

The term *destructured* is being increasingly used these days to denote soils that in their natural state are clearly influenced by structure of some sort, but that have been treated or manipulated in such a way that bonds between particles or any other structural effects have been eliminated. Its meaning is essentially the same as remolded, but it is intended to indicate that bonds or other forms of attachment between particles have been removed but the particles themselves are still intact. Remolding, on the other hand, means simply that the soil has been thoroughly reworked, and in the case of residual soils may mean that the particles themselves have been destroyed along with the structure. In this context we should note that some residual soils are not strictly particulate, that is, they do not consist of discrete individual particles. To the naked eye they may appear to consist of individual particles, but when remolded these particles disintegrate to form a collection of much smaller particles.

1.4 SPECIAL CLAY MINERALS

Apart from structure as a distinctive feature of many residual soils, geotechnical engineers should be aware of a group of very unusual clay minerals found only in residual soils. These are the two minerals, allophane and imogolite, which are normally linked together, and a third called halloysite. The extremely unusual properties of soils containing these minerals, especially allophane, can be a source of considerable puzzlement to engineers encountering them for the first time.

A good example of this is the story of the Sasamua dam built in Kenya in the 1950s. A fairly comprehensive account of the construction of the dam is given by Terzaghi (1958). The dam is built of tropical red clay containing a large proportion of the clay mineral halloysite. Investigations and laboratory testing for the project indicated that the clay did not conform to conventional behavior. In particular, it consisted of very fine-grained clay but had much higher shear strength than “normal” clays of similar particle size. Recognized authorities at the time, including Terzaghi, were called in to review the available data and provide specialist advice. As part of the review, they gathered information from several existing dams around the world believed to be built of similar soil. One of the dams was the Cipanunjang dam in West Java, Indonesia. It was built by Dutch engineers in 1927, and forms a water supply reservoir still in operation today. The author

reinvestigated this dam, purely out of curiosity, while working in Indonesia in the 1970s (Wesley 1974). Based on the performance of Cipanunjang and the other dams, Terzaghi and his team concluded that the soil was satisfactory, and the construction of the dam proceeded without difficulties.

The Cipanunjang dam in Indonesia is not actually built of red clay; it is built of a yellowish brown clay in which the predominant clay mineral appears to be allophane. However, it is weathered from volcanic ash and does contain some halloysite, so it has much in common with the Sasamua clay. Had the clay at Sasamua been similar to that at Cipanunjang, it would no doubt have raised even more concern as to its suitability for dam construction, since allophane clays frequently have extremely high water content, in the range of 75–200 percent. The Dutch engineers in 1927 were presumably happily unconcerned about whether their clay conformed to expected patterns of “normal” behavior. According to published records the engineers were actually building two earth dams at the time: one was Cipanunjang and the other was built out of a “normal” sedimentary clay. The latter suffered a major slope failure during construction. Cipanunjang, with its very unusual soil, was successfully completed, and is still in use today, as already indicated.

An important lesson from this story is that case records and observation of field behavior are generally more reliable guides to the geotechnical properties of a soil than a collection of field or laboratory test statistics. Examination of natural or cut slopes in soils of volcanic origin in the wet tropics (which include Kenya and Indonesia) shows them to remain stable at remarkably steep angles. This simple fact should take precedence over test data as a reliable indicator of their geotechnical properties and behavior. A more detailed account of the properties of volcanic clays is given in Chapter 9.

1.5 THE INFLUENCE OF TOPOGRAPHY

Topography has a strong and fairly consistent influence on the weathering process, and thus on the type of clay minerals formed, especially in the wet tropics. In hilly and mountainous areas, the soil is well drained and seepage flow has a strong downward component, as illustrated in Figure 1.4. This leads to the formation of low-activity clay minerals, especially kaolinite. In volcanic areas, as noted above, the minerals allophane and halloysite may be formed initially before ending up as kaolinite. Soils containing these minerals generally have good engineering properties. As Vaughan (1985) states, with some caution, “residual soils are generally quite well behaved.”

In wide, flat areas, drainage of any sort is much more limited, and moisture movement occurs primarily as a result of seasonal changes. Water is lost during dry periods from evaporation and the soil takes up moisture again

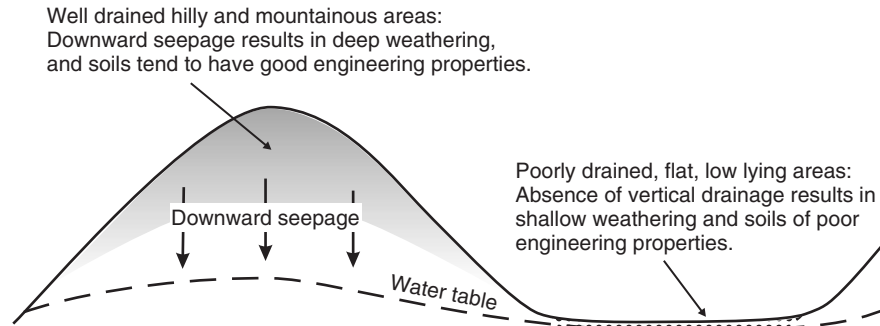


Figure 1.4 Influence of topography on residual soil formation.

during periods of rainfall. This environment tends to produce montmorillinite and associated high-activity clay minerals (smectites). Soils containing these minerals normally have poor or highly undesirable geotechnical properties. The term *vertisol* is used by soil scientists for these soils because the cyclic wetting and drying process and associated surface cracking tends to cause movement of soil as well as water in both the upward and downward, that is, vertical, direction close to the surface. The term *black clays* or *black cotton clays* is used in geotechnical literature for these soils.

1.6 GEOTECHNICAL ANALYSIS, DESIGN, AND THE ROLE OF OBSERVATION AND JUDGMENT

Some general comments are appropriate at this stage on the design process used in geotechnical engineering and the extent to which this may be influenced by residual soil properties. The term *design* is used here to mean the complete process by which the geotechnical engineer arrives at an answer to the question he or she is addressing. This may be the design of a foundation, the deformation of a retaining wall, or the stability of a natural hill slope. The design process can be considered (somewhat simplistically) to consist of the following steps:

1. Gathering basic information on soil conditions, that is, the geology of the site and the soil stratigraphy
2. Undertaking suitable tests, in the field, or in the laboratory, to determine soil properties, particularly the parameters needed for analysis
3. Carrying out an analysis by using the relevant parameters in an appropriate theoretical model, which could be a bearing capacity formula, a slip circle calculation, or highly sophisticated numerical modeling treating the soil as an elastic plastic nonlinear material

There is a growing tendency to think of the above steps as the complete design procedure, even to the extent that the analysis (i.e., the calculations) is thought of as the design. The advent of the computer and the increasing prevalence of design codes have accentuated this tendency. This view of design downgrades, or even leaves out entirely, the nonanalytical aspects of geotechnical design, namely observation, precedent, experience, and judgment, which are (or should be) essential components of all geotechnical design. The relative importance of the analytical component of design and the nonanalytical components varies depending on the situation. For the determination of the bearing capacity of a foundation on a homogeneous clay layer, the analysis could well be the principal component, but for the determination of the stability of a natural slope, the contribution of analysis may be quite insignificant compared with the roles of visual observation of the slope and geological appraisal.

Figure 1.5 shows two very elementary soil profiles: one of a sedimentary clay, and the other of a residual soil. It is possible that the sedimentary clay is essentially homogeneous, apart possibly from faint traces of horizontal bedding layers. However, it is unlikely that the residual soil profile is at all homogeneous, although there are situations where it may be so. It is much more likely to be heterogeneous, with a gradual change in properties with depth, and possibly containing joint or fault planes. Residual soils are thus less likely to be amenable to tidy analytical procedures than sedimentary soils, and the roles of observation, experience, and judgment become even more important parts of geotechnical engineering in residual soils.

Terzaghi once used the delightful phrase “the omnipotence of theory” in the following statement:

However, as soon as we pass from steel and concrete to earth, the omnipotence of theory ceases to exist. In the first place, the earth in its natural state is never uniform. Second, its properties are too complicated for rigorous theoretical treatment. Finally, even an approximate mathematical solution of some of the most common problems is extremely difficult (Terzaghi 1936).

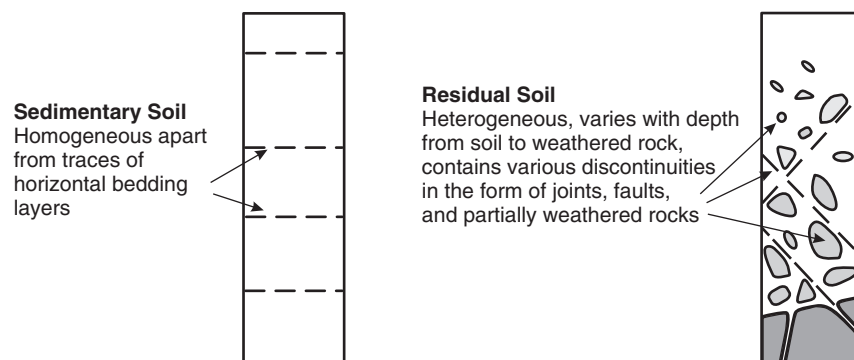


Figure 1.5 Simplified soil profiles in sedimentary and residual soils.

If the omnipotence of theory ceases to exist with sedimentary soils, then it inevitably declines even further with residual soils. However, we should not read more into Terzaghi's words than he presumably intended. He is not rejecting theory, only its omnipotence, and uses the term "theory" to denote the process of collecting a set of figures, introducing them into appropriate equations, and coming up with the required answer. Given this meaning, theory is not to be confused with fundamental concepts and principles and Terzaghi's statement should not be taken to mean that we can downgrade the latter.

1.7 SUMMARY OF BASIC DIFFERENCES BETWEEN RESIDUAL AND SEDIMENTARY SOILS

Although we have not yet covered them all, the most significant differences between residual soils and sedimentary soils can be summarized as follows:

1. Residual soils are generally more heterogeneous than sedimentary soils.
2. Because they have not been formed by a sedimentation process, stress history is an irrelevant concept and not a significant influence on residual soil behavior.
3. The theoretical framework for understanding sedimentary soils involving the e -log p plot and the division into normally consolidated and overconsolidated soils is not applicable to residual soils.
4. Some residual soils, especially those of volcanic origin, may have unusual properties due to the presence of clay minerals not found in sedimentary soils.
5. Some residual soils in their undisturbed state are not strictly particulate, that is, they do not consist of discrete particles. Such soils may appear to consist of individual particles, but when the soil is disturbed or remolded the particles disintegrate into smaller particles.
6. Empirical correlations between soil properties developed from the study of sedimentary soils may not be valid when applied to residual soils.
7. The water table in residual soils is often relatively deep, and subject to fluctuations from climatic effects. This means that much of the action of interest to geotechnical engineers takes place above the water table, and an understanding of the pore pressure regime above the water table becomes an important component to understanding residual soil behavior.
8. In evaluating the properties of residual soils it is very important to first observe carefully their behavior in the field, before looking at the results of laboratory tests.

REFERENCES

- Gasparre, A., M. R. Nishimurai, M. R. Coop, and R. J. Jardine. 2007. The influence of structure on the behaviour of London Clay. *Geotechnique* 57: 19–31.
- Maccarini, M. 1987. *Laboratory Studies of Weakly Bonded Artificial Soil*. Thesis, University of London.
- Terzaghi, K. 1936. Presidential address. *First International Conference on Soil Mechanics and Foundation Engineering*. Cambridge, Massachusetts, USA.
- Terzaghi, K. 1958. Design and performance of the Sasumua dam. *Proceedings, the Institution of Civil Engineers*. London, April, Vol. 9, 369–396.
- Toll, D. G., V. Malandraki, Z. Ali Rahman, and D. Gallipoli. 2006. Bonded soils: problematic or predictable? *Proceedings 2nd International Conference on Problematic Soils, Malaysia*. Ci-Premier Pte Ltd, 55–62.
- Vaughan, P. R. 1985. Mechanical and hydraulic properties of in situ residual soils. *Proceedings, First International Conference on Geomechanics in Tropical, Lat-eritic, and Saprolitic Soils, Brazil*, 1–33.
- Wesley, L. D. 1974. Cipanunjang (Tjipanundjang, old spelling) Dam in West Java, Indonesia. *Journal of the Geotechnical Division ASCE100/GT5*: 503–522.
- Wesley, L. D. 2009. *Fundamentals of Soil Mechanics for Sedimentary and Residual Soils*. New York: Wiley.
- Zhang, G., A. J. Whittle, J. T. Germaine, and M. A. Nikolinakau. 2007. Characterisation and engineering properties of an old alluvium in Puerto Rico. *Proceedings, Characterisation and Engineering Properties of Natural Soils*, Vol. 4, 2557–2588. Leiden, The Netherlands: Taylor & Francis/Balkema.