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CONTENTS

Chapter 30

Tropical soils

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Tropical soils are formed primarily by *in situ* weathering processes, and hence are residual soils. Terminology for tropical soils is confused and many classification schemes exist, based on either pedological, geochemical or engineering criteria. For classification schemes to be useful they need to include the effects of disintegration due to weathering, mineralogy (particularly the 'unusual' clay minerals that are particular to tropical soils), cementation and structure. Tropical residual soils are highly structured materials, both at macro and micro levels. The micro-structure is produced by leaching out of minerals during weathering, leaving an open structure. Tropical soils are also likely to be cemented soils due to deposition of minerals either during or after weathering. The highly structured nature of tropical soils, combined with the fact, they often exist in an unsaturated state, makes them difficult to deal with as engineering materials. However, they often have good engineering properties. Nevertheless, some tropical soils can be problematic, demonstrating collapse or shrink–swell movements. Ground investigation for tropical soils poses some difficulties due to their heterogeneous nature. Sampling of tropical soils so that the original structure is maintained can be a major challenge, and hence there is a strong emphasis on *in situ* testing methods.

30.1 Introduction

Tropical soils are formed primarily by *in situ* weathering processes, and hence are *residual soils*. The climatic conditions in tropical regions, with high temperatures and high levels of precipitation, lead to stronger chemical weathering of primary minerals and a greater penetration of weathering than occurs in other regions of the Earth (**Figure 30.1**).

The weathering process propagates from the Earth's surface and is controlled primarily by water movement within the joints of the parent rock. Weathering starts on the joint surfaces and progressively penetrates into the rock mass. The direction of propagation of a weathered profile will be dictated by the direction of the joints, so while there is likely to be a vertical component, weathering can also progress horizontally or at other inclinations.

Weathering is usually defined by the degree of decomposition/disintegration of the rock to form soil. This is rated as Grade I (*fresh rock*) through to Grade VI (*residual soil*), where the rock has fully decomposed to form soil. This weathering scale will be discussed in more detail below. The upper three grades, VI (*residual soil*), V (*completely weathered*) and IV (*highly weathered*), represent a material where more than 50% of the rock has decomposed to form soil; the term *tropical residual soil* is used to describe these upper three weathering grades that are dominated by soil material (note the distinction between ***tropical*** *residual soil*, which incorporates all three weathering grades IV, V and VI, and *residual soil,* which only describes Grade VI). The term *saprolite* is used to describe completely and highly weathered material, i.e. a soil which

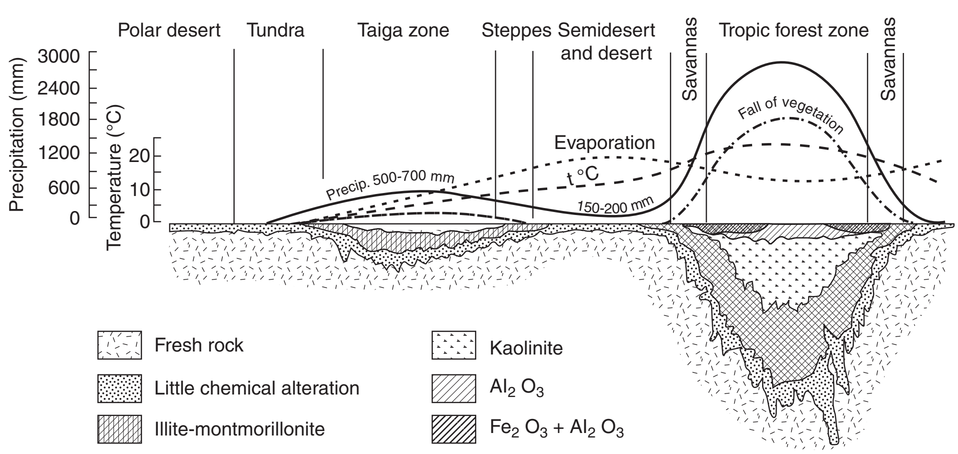

Figure 30.1 Depth of residual soil development related to climatic factors. Weathering may penetrate to greater than 30 m in tropical regions
Reproduced from Strakhov (1967)

still contains some unweathered rock, but does not incorporate the fully decomposed Grade VI.

The particle size distribution (grading) of tropical soils can be highly variable. Early stages of weathering are likely to produce coarser-grained soils. Large boulder- or cobble-sized fragments of unweathered material may still survive as corestones. Stronger chemical weathering will cause minerals such as feldspar and mica to decompose to form clay minerals, so the resulting residual soil may be more fine-grained. The resulting grain size distribution after weathering will depend on the parent rock. For instance, acidic igneous rocks (e.g. granite) contain a high proportion of silica that will resist weathering, so the resulting soil will contain sand-sized silica particles. **Table 30.1** shows the types of residual soil resulting from different parent rocks.

A common feature of many tropical soils is the presence of iron or aluminium oxides, often referred to as sesquioxides (Fe_2O_3 or Al_2O_3). This produces the reddish coloration common to many tropical soils. Iron and aluminium oxides released by weathering are not dissolved as in more acidic environments and remain *in situ*. Iron oxide is crystallised as haematite when the soil is seasonally desiccated, or as goethite in a constantly humid environment; haematite gives the soil a red colour, goethite a brown or ochreous colour. Gibbsite is the main aluminium oxide formed. During the weathering process, silica and bases (K, Na, Ca, Mg) are lost in solution or incorporated into clay minerals.

The term *laterite* has been used to describe a wide range of red soils, and the term has become almost meaningless in an engineering sense. It was used originally to describe a red clay which hardened irrecoverably on exposure to air, but has subsequently been used to describe almost any soil with reddish coloration. The term *laterite* will be used here to refer to a soil with a high degree of iron cementing and the term *red tropical soil* will be used for a soil that has red coloration but without significant cementing.

The weathering process can be divided into three stages based on the mineralogical and geochemical changes (Duchaufour, 1982). These stages are based on the dominant clay minerals that are produced by weathering:

(1) fersiallitisation (smectite clays dominant);

(2) ferrugination (kaolinite and smectites);

(3) ferrallitisation (kaolinite and gibbsite).

As weathering proceeds (ferrugination–ferrallitisation) there is a decrease in concentration of silica and bases and an increase in concentration of iron and aluminium oxides. The resulting soil at the final stage of weathering (ferrallitic soil) is clay-rich and also rich in sesquioxides.

The iron, in the presence of negatively charged clay particles, may be present in the reduced form as ferrous oxide (FeO). Ferrous (Fe^{2+}) iron is soluble and highly mobile, whereas ferric (Fe^{3+}) iron is virtually insoluble. If oxidising conditions become present (such as exposure to air in an excavation or by lowering of the groundwater table) the soluble ferrous iron is precipitated as ferric oxides (Fe_2O_3) such as goethite or limonite. This results in an indurated soil, i.e. a soil that becomes harder through cementation. Alternating reduction and oxidation due to fluctuating groundwater levels in the geological past leads to the development of concretionary or nodular laterites.

Indurated, rock-like *duricrusts* can be formed by cementing of tropical soils by a number of chemicals. Iron and aluminium oxides or silica released during weathering, or calcium carbonate, can be moved laterally or vertically through the soil profile by groundwater flow and may accumulate sufficiently in some horizons for crystallisation to occur, resulting in duricrust formation.

Terminology for tropical soils is confused and many classification schemes exist, based on either pedological, geochemical or engineering criteria. The classification given by Duchaufour (1982), based on weathering stages, has been adopted as the basis of a Working Party Report by the Geological Society (Anon., 1990), later published by Fookes (1997). However, it will be argued that there are other factors, such as weathering grade, degree of cementation and mass structure, that are equally important.

Tropical residual soils are often highly structured materials, both at macro and micro levels. The micro-structure is produced by leaching out of minerals during weathering, leaving an open structure, combined with the effects of secondary cementing by minerals deposited during or after weathering has taken place. The cementing (bonding) can maintain the fabric of the soil in a metastable state, i.e. such a loose structure could not exist if the bonding was not present to support it. **Figure 30.2** shows a typical example of the micro-structure of a residual soil from Singapore. The open fabric can be clearly seen as well as a variation in the degree of cementing within the soil.

Parent rock	Residual soil type	Relative susceptibility to tropical weathering
Calcareous rock (limestone, dolomite)	Gravel in clayey or silty matrix	1 (most vulnerable)
Basic igneous rock (gabbro, dolerite, basalt)	Clay (often grading into sandy clay with depth)	2
Acid crystalline rock (granite, gneiss)	Clayey sand or sandy clay (often micaceous)	3
Argillaceous sedimentary rock (mudstone, shale)	Silt or silty clay	4
Arenaceous sedimentary or metamorphic rock (sandstone, quartzite)	Sand (clayey sand in the case of residual arkose or feldspathic sandstone)	5 (least vulnerable)

Table 30.1 Types of residual soil from different parent rocks
Data taken from Brink *et al.* (1982)

Tropical soils have a reputation for being 'problematic'. This is because they do not conform to the widely used classification systems that have been developed for temperate sedimentary soils to identify likely engineering behaviour. They are also difficult to investigate, as attempts to sample or test them can destroy the cementing and structure that supports them. This chapter will identify the problems in classifying and investigating tropical soils, and identify schemes and methods that are appropriate for tropical soils.

Of course, some tropical soils can be highly problematic. Residual soils can exist in a loose, structured state and can collapse on loading, or due to wetting, leading to sudden settlements. Other problematic types of tropical soil contain highly expansive smectite clays, resulting in significant heave or shrinkage as wetting or drying occurs. These aspects of behaviour of tropical soils will be considered in a range of applications: foundations, slopes and highways.

30.2 Controls on the development of tropical soils

30.2.1 Weathering processes

One of the most important factors in the engineering behaviour of tropical soils is the degree of weathering. Little (1969) first proposed a six-grade classification for tropical residual soils. This has become the well-established scheme for identifying the degree of rock weathering used in the Geological Society Working Party Report on Core Logging (Anon., 1970) and the Working Party Report on Rock Mass Description (Anon.,

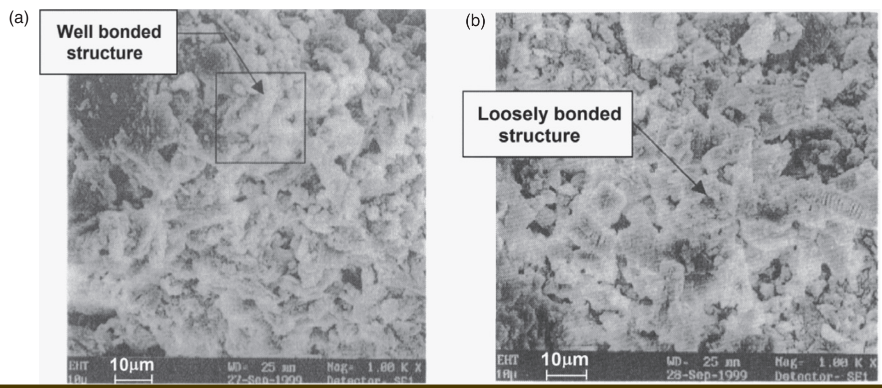

Figure 30.2 Scanning electron microscope images showing the micro-structure of a tropical residual soil from Singapore: (a) well bonded with strong cementing; (b) looser structure
Reproduced from Aung *et al*. (2000)

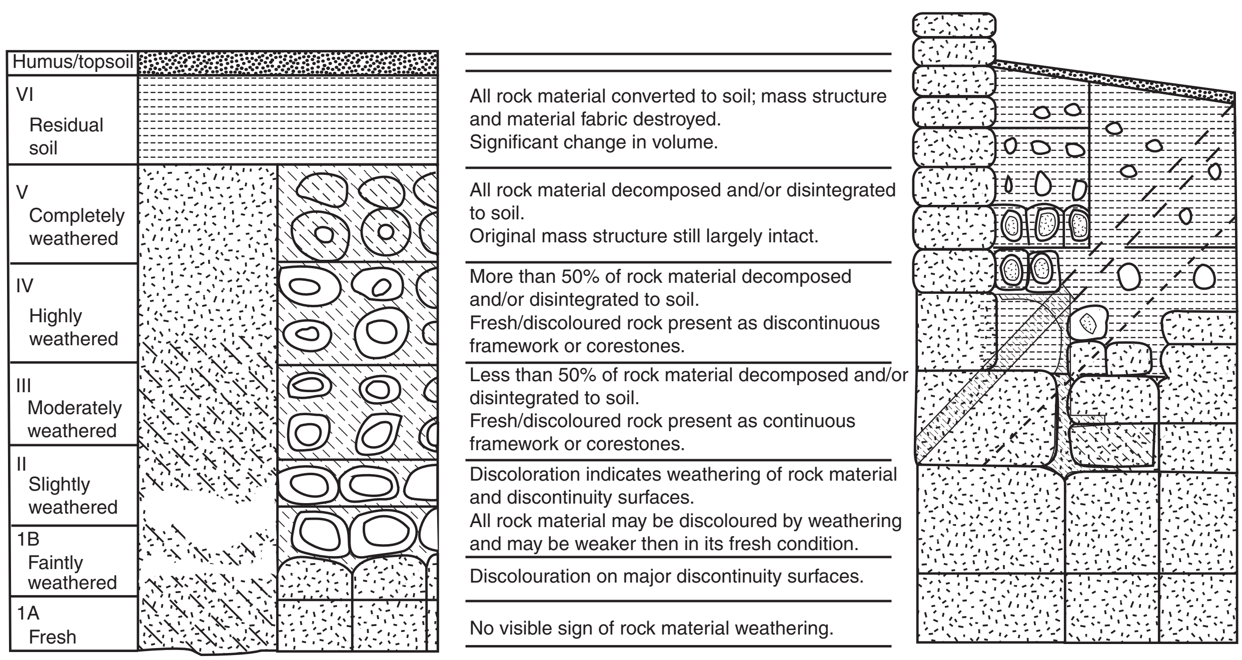

Figure 30.3 Schematic diagrams of typical weathering profiles
Reproduced from Anon. (1990) © The Geological Society

1977). This was the scheme used in ISRM (1978), whereby the relative percentages of 'rock' that has decomposed/disintegrated to form 'soil' are used to define the weathering grade. **Figure 30.3** shows a useful diagrammatic representation of the scheme.

British Standard BS 5930 (British Standard Institution, 1999) provided an alternative method to characterise the degree of weathering by identifying weathering grades based on three approaches, as shown in **Figure 30.4**. However, the British Standard was superseded by Eurocode documents for soil

APPROACH 1: FACTUAL DESCRIPTION OF WEATHERING (MANDATORY)

Standard descriptions should always include comments on the degree and nature of any weathering effects at material or mass scales. This may allow subsequent classification and provide information for separating rock into zones of like character. Typical indications of weathering include:

- Changes in colour
- Reduction in strength
- Changes in fracture state
- Presence, character and extent of weathering products

These features should be described using standard terminology, quantified as appropriate, together with non-standard English descriptions as necessary to describe the results of weathering. At the mass scale the distribution and proportions of the variously weathered materials (e.g. corestones vs matrix) should be recorded.

Can classification be applied unambiguously? — No → Do NOT CLASSIFY

Yes ↓

Rock is moderately strong or stronger in fresh state

APPROACH 2: CLASSIFICATION FOR UNIFORM MATERIALS

Grade	Classifier	Typical characteristics
I	Fresh	Unchanged from original state
II	Slightly weathered	Slight discoloration, slight weakening
III	Moderately weathered	Considerably weakened, penetrative discoloration Large pieces cannot be broken by hand
IV	Highly weathered	Large pieces cannot be broken by hand Does not readily disaggregate (slake) when dry sample immersed in water
V	Completely weathered	Considerably weakened Slakes Original texure apparent
VI	Residual soil	Soil derived by *in situ* weathering but retaining none of the original texure of fabric

Is a zonal classification appropriate and is there enough information available? — No → Use Rock Mass Classification if appropriate

Yes ↓

APPROACH 3: CLASIFICATION FOR HETEROGENOUS MASSES

Zone	Proportions of material grades	Typical characteristics
1	100% G I – III (not necessarily all fresh rock)	Behaves as rock: apply rock mechanics principles to mass assessment and design
2	> 90% G I – III < 10% G IV – VI	Weak materials along discontinuities. Shear strength stiffness and permeability affected
3	50% to 90% G I – III 10% to 50% G IV – VI	Rock framework still locked and controls strength and stiffness; matrix controls permeability
4	30% to 50% G I – III 50% to 70% G IV – VI	Rock framework contributes to strength: matrix or weathering products control stiffness and permeability
5	< 30% G I – III > 70% G IV – VI	Weak grades will control behaviour. Corestones may be significant for investigation and construction
6	100% G IV – VI (not necessarily residual soil)	May behave as soil although relict fabric may still be significant

Rock is moderately weak or weaker in fresh state

APPROACH 4: CLASSIFICATION INCORPORATING MATERIAL AND MASS FEATURES

Class	Classifier	Typical characteristics
A	Unweathered	Original strength, colour, fracture spacing
B	Partially weathered	Slightly reduced strength, slightly closer fracture spacing, weathering penetrating in from fractures, brown oxidation
C	Distinctly weathered	Further weakened, much closer fracture spacing, grey reduction
D	Destructured	Greatly weakened, mottled, ordered lithorelics in matrix becoming weakened and disordered, bedding disturbed
E	Residual or reworked	Matrix with occasional altered random or 'apparent' lithorelics, bedding destroyed Classed as reworked when foreign inclusions are present as a result of transporations

APPROACH 5: SPECIAL CASES

For rocks whose weathering state does not follow the other patterns indicated here, such as karst in carbonates, and the particular effect of arid climates

Figure 30.4 Description and classification of weathered rock for engineering purposes
Reproduced with permission from BS 5930 © British Standards Institution 1999

and rock description in April 2010. EN 14689-1:2003 (British Standard Institution, 2003) for rock description returned to the scheme illustrated in **Figure 30.3**. Hencher (2008) saw this transition from the BS approach to the EN definitions as a retrograde step. As will be discussed later, in section 30.3.2, a full classification of tropical soils must include more than just the weathering grade, and should also incorporate mineralogy, secondary cementation and structure.

As has been noted, Duchaufour (1982) identified three phases of development in the weathering process, based in changes in mineralogy and geochemistry, as opposed to the degree of decomposition/disintegration:

(1) fersiallitisation;

(2) ferrugination;

(3) ferrallitisation.

As weathering proceeds (fersiallitisation–ferrugination–ferrallitisation) there are changes in mineralogical composition, in particular the formation of clay minerals. This is associated with a decrease in concentration of silica and bases (K, Na, Ca, Mg) and an increase in concentration of iron and aluminium oxides. Fersiallitic soils are dominated by 2:1 clay minerals (smectites). The main clay mineral present in ferruginous soils is kaolinite (1:1) although some smectite may be present. Ferrallitic soils are dominated by kaolinite and gibbsite (aluminium oxide).

Clay minerals are alumina-silicates that are made up of sheets comprising either silica tetrahedrons (tetrahedral sheets) or alumina octahedrons (octahedral sheets). 1:1 clay minerals are made up of alternating tetrahedral and octahedral sheets. The adjacent layers are closely bonded together, preventing water molecules from penetrating between the sheets. This makes them relatively low-activity minerals (i.e. low shrinkage/swelling). 2:1 clay minerals have one octahedral sheet sandwiched between two tetrahedral sheets. Adjacent layers are not held together strongly, thus allowing water molecules to penetrate between sheets, resulting in high-activity minerals (i.e. high shrinkage/swelling).

Duchaufour's stages of weathering are shown in **Table 30.2**, together with comparisons with other pedological schemes and commonly used geotechnical descriptive terms. Duchaufour's scheme was adopted by a Geological Society Working Party Report on Tropical Soils (Anon., 1990; Fookes, 1997) for its classification of tropical soils, as will be discussed in section 30.3.2.

30.2.2 Parent rock

The type of residual soil will depend on the parent rock. Some typical examples of residual soil types are given in **Table 30.1**. Also shown are the relative susceptibilities to weathering in a tropical environment (Brink *et al.*, 1982).

30.2.3 Climate

The stage of weathering which is achieved is controlled by the climate. The effect of climate on the weathering products is shown in **Table 30.3**.

Reference	Rainfall (mm per annum)	Clay mineral type
Pedro (1968)	< 500	Montmorillonite
	500–1200/1500	Kaolinite dominant
	> 1500	Gibbsite and kaolinite
Sanches Furtado (1968)	800–1000	Kaolinite and montmorillonite
	1000–1200	Kaolinite dominant
	1200–1500	Kaolinite and gibbsite

Table 30.3 Climate and weathering products
Data taken from McFarlane (1976)

Pedological classifications			Common geotechnical terminology	Colour	Mineralogy
Duchaufour	USA	FAO/ UNESCO			
VERTISOL (fersiallitic)	Vertisol	Vertisol	Black Cotton soil	Black, brown, grey	Smectites (montmorillonite), kaolinite
ANDOSOL (fersiallitic)	Inceptisol	Andosol	Halloysite/ Allophane soil	Red, yellow, purple	Kaolinite (halloysite), allophane
FERRUGINOUS	Alfisol	Nitosol, alfisol, lixisol	Red tropical soil	Red, yellow, purple	Kaolinite, hydrated iron oxide (haematite, goethite), hydrated aluminium oxide (gibbsite)
FERRISOL (transitional)	Ultisol	Ferralsol	Lateritic soil, latosol	Red, yellow, purple	Kaolinite, Hydrated iron oxide (haematite, hoethite), hydrated aluminium oxide (gibbsite)
FERRALLITIC	Oxisol	Plinthisol	Plinthite, laterite	Red, yellow, purple	Kaolinite, Hydrated iron oxide (haematite, goethite), hydrated aluminium oxide (gibbsite)

Table 30.2 Terminology for tropical soils

The phases of weathering defined by Duchaufour (1982) can also be related to climate. In Mediterranean or sub-tropical climates with a marked dry season, stage 1 (fersiallitisation) is rarely exceeded. In a dry tropical climate development stops at stage 2 (ferrugination). Only in humid equatorial climates is stage 3 (ferrallitisation) reached (see **Table 30.4**).

The world distributions of the major types of tropical residual soils are shown in **Figure 30.5**. Fookes (1997) notes that these broad classes of soils extend beyond the tropics in favourable conditions. Examples are ferrallitic soils on high-rainfall sub-tropical continental east coasts, and fersiallitic soils in west coast/Mediterranean and continental interiors in mid-latitudes.

The development of duricrusts (rock-like cemented/indurated soils) is also highly dependent on climatic conditions. Ackroyd (1967) presents possible conditions under which the different stages of concretionary material develop in ferricrete (or laterite) (**Table 30.5**). The climate is categorised using the Thornthwaite moisture index (Thornthwaite and Mather, 1954). This provides a way of defining climatic conditions based on the difference between the precipitation and evapotranspiration expressed as a ratio to the potential evapotranspiration. A negative value indicates a dry environment and positive values indicate more humid environments.

Phase	Soil type	Zone	Mean annual temperature (°C)	Annual rainfall (m)	Dry season
1	Fersiallitic	Mediteranean, subtropical	13–20	0.5–1.0	Yes
2	Ferruginous Ferrisols (transitional)	Subtropical	20–25	1.0–1.5	Sometimes
3	Ferrallitic	Tropical	> 25	> 1.5	No

Table 30.4 Summary of Duchaufour's residual soil phases in relation to climate factors
Data taken from Anon (1990)

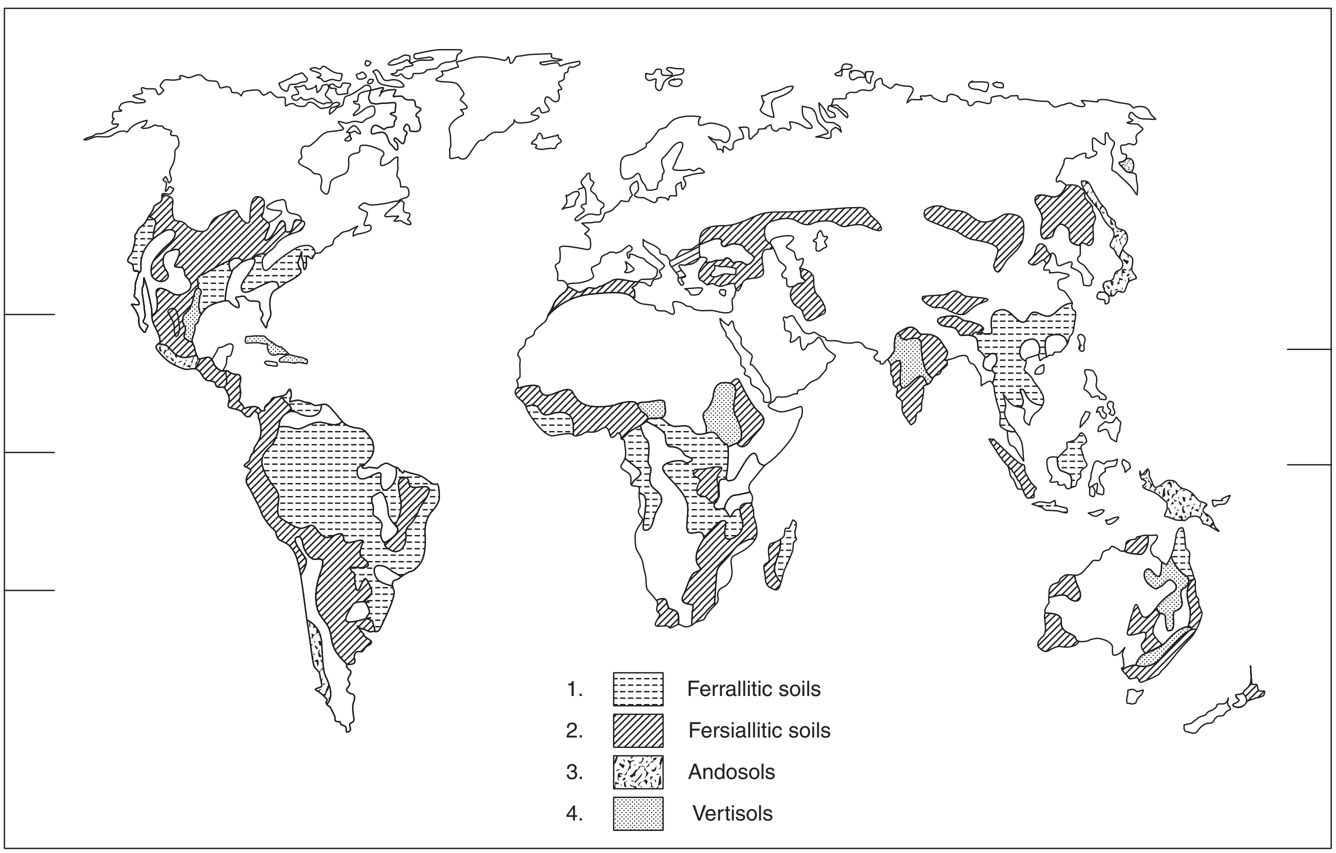

Figure 30.5 Simplified world distribution of tropical residual soils
Based on FAO World Soil Map (Fookes, 1997)

However, McFarlane (1976) points out that the conditions for development of concretions are not the conditions under which the laterite minerals initially form. McFarlane identified a model of laterite formation based on a fluctuating groundwater table in an overall downward flow environment. A cycle of development may result, where the original lateritic deposit is weathered, producing iron and aluminium oxides that are mobilised and recrystallised elsewhere to form a new laterite deposit.

30.2.4 Relief and drainage

Relief and drainage have major effects on the stages of weathering. Idealised soil profiles (catenas) are shown for three rock types in **Figure 30.6**. However, these simple catenary sequences will be modified by the drainage conditions. If the base of the slope is poorly drained, then fersiallitic soils will develop even on acid crystalline rocks. Equally if drainage conditions are good then ferrallitic soils may develop on basic rocks.

30.2.5 Secondary cementation

Many tropical soils are bonded due to the presence of chemical cementing agents. These chemicals may develop by pedogenic processes induced by the accumulation of iron or aluminium oxides (as they are released during weathering) or the movement of leached silica, aluminium and iron oxides, gypsum or carbonates by groundwater flow. These minerals may accumulate sufficiently in some horizons for crystallisation to occur.

The resulting harder varieties of pedogenic materials such as calcrete, silcrete, ferricrete and alucrete are known as duricrusts or pedocretes. The cementing agents for each type of duricrust are identified in **Table 30.6**.

Netterberg (1971) categorised calcretes into calcified material, powder calcrete, nodular calcrete and hardpan calcrete, and showed that the engineering properties were highly dependent on the type of calcrete. Charman (1988) adopted a similar classification scheme for laterite (or ferricrete) (**Table 30.7**).

Different stages of laterisation are reflected in the silica/alumina ratio (SiO_2/Al_2O_3) (Desai, 1985). Typical values are given in **Table 30.8**.

	Annual rainfall (mm)		
	750–1000	1000–1500	1500–2000
Thornthwaite moisture index	–40 to –20	–20 to 0	0 to +30
Length of dry season (months)	7	6	5
Type of product	Rock laterite or cuirasse	Hard concretionary gravels	Minimum requirements for concretions to develop

Table 30.5 Possible conditions for development of concretionary laterite

30.3 Engineering issues

30.3.1 Investigation

Ground investigation for tropical soils poses some difficulties due to the heterogeneous nature of tropical residual soils. The soil properties will be dependent on the degree of weathering, which varies within the weathered mass; there can often be 'corestones' of relatively unweathered rock (which can be of cobble or boulder size) contained within a matrix of more

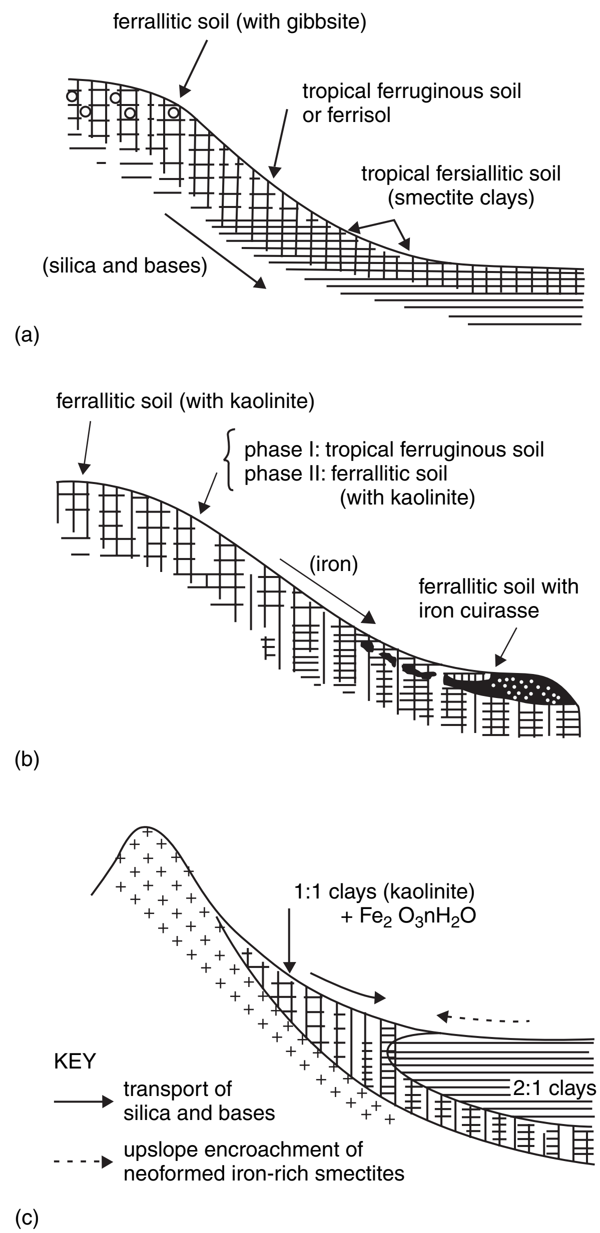

Figure 30.6 Simple soil catenas for different rock types: (a) basic volcanic rocks in a humid tropical climate; (b) acid crystalline rocks in a humid tropical climate; (c) around inselbergs in the tropics (Inselbergs are prominent steep-sided hills of resistant igneous rock rising out of a flat plain)

Reproduced from Fookes (1997) (from Duchaufour, 1982) weathered material. The original rock mass structure, such as joint sets, will be represented in relict form in the tropical residual soil and can represent planes of weakness (Irfan and Woods, 1988; Au, 1996).

The overall degree of weathering will vary from the highest degree of weathering near the ground surface to less weathered and possibly fresh rock deeper within the ground mass. However, the changes between grades of weathering will be progressive; there are unlikely to be sharp distinctions between layers of different weathered materials, so identification of boundaries between weathering grades can be highly subjective.

In addition to this, the degree of secondary cementing can be highly variable, both in terms of the amount of the cementing minerals (e.g. iron oxides) and the strength of the cemented bonds. The 'structured' nature of tropical soils (Vaughan, 1985a) makes them particularly sensitive to disturbance during sampling and testing.

Duricrust	Cementing mineral
Silcrete	Silica
Calcrete	Calcium or magnesium carbonate
Gypcrete	Calcium sulphate dihydrate
Alucrete (bauxite)	Hydrated aluminium oxides
Ferricrete (laterite)	Hydrated iron oxides

Table 30.6 Duricrusts and their cementing minerals

Sampling of residual soils so that the original structure is maintained can be a major challenge. Driven or pushed samplers are likely to cause significant breakdown of the structure, resulting in samples that no longer represent the *in situ* conditions. Large block samples, trimmed by hand, may be the only way to get satisfactory samples. Details of sampling procedures are outlined in Fookes (1997).

There has been success with using rotary coring techniques, using triple-tube core barrels and air foam flush to recover good quality samples (Phillipson and Brand, 1985; Phillipson and Chipp, 1982). Mazier core barrels (73 mm diameter) are commonly used, as are Treifus triple-tube barrels (63 mm diameter). Plastic lining tubes should be used to protect the core on extrusion. Water drilling flush should not be used, as the flushing medium can cause erosion of the core or result in changes in water content. Even compressed air flush can potentially change the suctions in samples (Richards, 1985).

Due to the difficulties in recovering high-quality, undisturbed samples, there has been a strong emphasis on *in situ* testing to determine the engineering properties of tropical soils. Pressuremeter and plate load tests are suitable tests for assessing *in situ* properties. Standard penetration testing (SPT) is also widely used. Cone penetration testing (CPT) and vane testing are unlikely to be suitable for weathered profiles containing significant amounts of rock material, as penetration of

Age	Recommended name	Characteristic	Equivalent terms in the literature
Immature (young)	PLINTHITE	Soil fabric containing significant amount of lateritic material. Hydrated oxides present at expense of some soil material. Unhardened, no nodules present but may be slight evidence of concretionary development	Plinthite Laterite Lateritic clay
	NODULAR LATERITE	Distinct hard concretionary nodules present as separate particles	Lateritic gravel Ironstone Pisolitic gravel Concretionary gravel
	HONEYCOMB LATERITE	Concretions have coalesced to form a porous structure which may be filled with soil material	Vesicular laterite Pisolitic ironstone Vermicular ironstone Cellular ironstone Spaced pisolitic laterite
Mature (old)	HARDPAN LATERITE	Indurated laterite layer, massive and tough	Ferricrete Ironstone Laterite crust Vermiform laterite Packed pisolitic laterite
	SECONDARY LATERITE	May be nodular, honeycomb or hardpan, but is the result of erosion of pre-existing layer and may display brecciated appearance	

Table 30.7 Classification of laterite
Data taken from Charman (1988)

the testing device will be restricted. However, these techniques may be suitable for Grade VI residual soils.

The pressuremeter has been used for the investigation of properties of tropical soils (e.g. Schnaid and Mantaras, 2003). However, as Schnaid and Huat (2012) note, the pressuremeter response curve will be dependent on a combination of *in situ* horizontal stress, soil stiffness and strength parameters, and these parameters will reduce with destructuration at high shear strains. Schnaid and Huat suggest that, in residual soils, the pressuremeter should be viewed as a 'trial' boundary value problem against which a theoretical pressure-expansion curve predicted using a set of independently measured parameters can be compared to field pressuremeter tests. A good comparison between a number of observed and predicted curves can give confidence that the selected parameters used in the prediction are sensible, and can therefore be adopted in design. An example of a pressuremeter test carried out in a Brazilian residual soil reported by Schnaid and Mantaras (2003) is compared against a numerical simulation in **Figure 30.7** and shows that good agreement can be achieved.

Stage of laterisation	SiO_2/Al_2O_3
Unlaterised soil	> 2
Lateritic soil	1.3–2
Laterite	< 1.3

Table 30.8 Typical values for silica/alumina ratio
Data taken from Desai (1985)

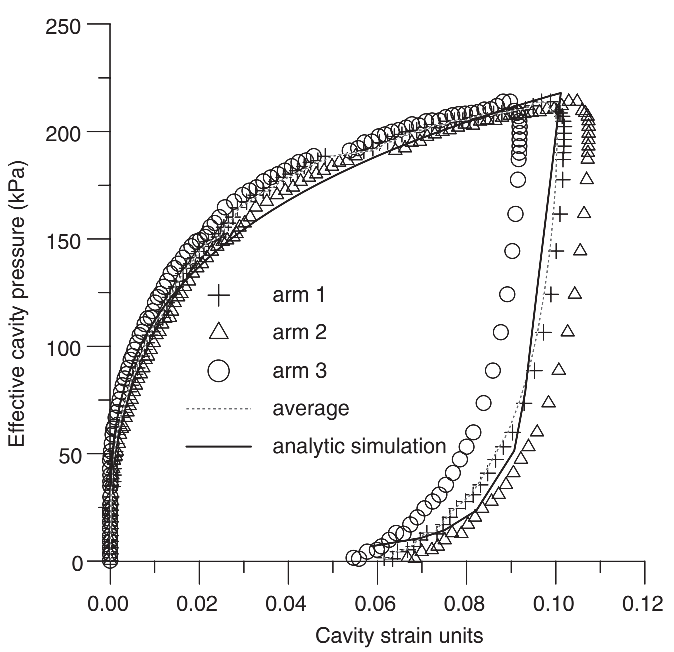

Figure 30.7 An example of a pressuremeter test carried out in saprolite from Brazil compared to an analytical simulation
Data taken from Schnaid and Mantaras (2003)

Plate load testing is a popular option for assessing tropical soils as it has the advantage of testing a larger volume of material, thereby giving a measure of the mass behaviour of a heterogeneous soil. Procedures for performing such tests are described by Barksdale and Blight (1997). The results can be used primarily to estimate the stiffness or compressibility of the soil. The interpretation of the results may be complicated by the structured nature of the soils and unsaturated state, as both factors will influence the initial soil stiffness and the yield stress observed. Schnaid and Huat (2012) suggest that interpretation of test data may require sophisticated numerical analysis with appropriate constitutive models, rather than the conventional interpretation methods commonly used to estimate the elastic modulus.

Standard penetration tests are widely used around the world for assessing the relative density and hence the angle of shear resistance of soils, based on empirical correlations. It has to be recognised that such correlations have usually been established from databases of tests on sedimentary soils. They are unlikely to be appropriate for tropical residual soils as they take no account of any cementing/bonding that influences the strength of the soil. Local relationships may need to be determined for a particular tropical soil that take account of the cementing and local variability.

Schnaid *et al*. (2004) have suggested that cementation of residual soils can be observed by considering the ratio of the elastic stiffness to ultimate strength, G_0/N_{60}, where G_0 is the shear modulus at very small strains and N_{60} is the SPT test value standardised to a reference value of 60% of the potential energy of the SPT hammer. They plotted this ratio against $(N_1)_{60}$, where the N_{60} value is normalised to take account of the vertical effective stress and hence should give a closer indication of relative density of the deposit. They found that the bonded structure has a marked effect for residual soils, producing values of normalised stiffness (G_0/N_{60}) that are considerably higher than those observed in fresh uncemented materials.

30.3.2 Classification

The search for an appropriate scheme for classifying tropical soils has occupied engineering geologists, geotechnical engineers, pedologists and soil scientists for many years. A proliferation of such schemes exist: the Geological Society Working Party Report on Tropical Soils (Anon., 1990; Fookes, 1997) tabulates over 20 different schemes developed between 1951 and 1986, each with a different end use in mind. Although a number of well-developed pedological schemes exist, they are not always relevant for classifying tropical soils for engineering use. Leong and Rahardjo (1998) conclude that, in spite of the efforts to develop classification schemes by geologists, pedologists and engineers, no suitable classification system exists for the study of residual soils.

The Geological Society Working Party Report on Tropical Soils (Anon., 1990; Fookes, 1997) represents the most complete attempt to produce a useful classification scheme for tropical soils. The Working Party opted for a purely pedogenic classification scheme based on the work of Duchaufour (1982) (**Table 30.2**).

Another major work on residual soils (Blight, 1997) proposes a rather different classification scheme (Wesley and Irfan, 1997). They identify the factors influencing residual soil behaviour as:

- physical composition (e.g. percentage of unweathered rock, particle size distribution, etc.);
- mineralogical composition;
- macro-structure (layering, discontinuities, fissures, pores, etc. discernible to the naked eye);
- micro-structure (fabric, inter-particle bonding or cementation, aggregation, etc.).

To take these factors into account they suggest grouping soils into three types (**Table 30.9**).

According to Wesley and Irfan, Group A (which is not strongly influenced by particular clay minerals) is typical of many tropical soil profiles. The group is further sub-divided by structure components (macro-structure dominated, micro-structure dominated or soils not significantly influenced by either). They suggest that the engineering properties of Group B (which includes vertisols) will be very similar to transported soils with the same clay mineralogy. Group C, which is dominated by minerals only found in tropical soils (halloysite, allophane and aluminium and iron sesquioxides) is sub-divided according to the minerals present.

A way to incorporate these different aspects is proposed by the author of this chapter, where the four factors of disintegration, mineralogy, cementation and structure (DMCS) are encoded on a six-point scale for each factor. It is suggested that the four factors are depicted as shown in **Figure 30.8** using the scales listed in **Table 30.10**. A higher number in each category indicates a more problematic material.

Major division		Sub-group
Group A	Soils without a strong mineralogical influence	(a) Strong macro-structure influence (b) Strong micro-structure influence (c) Little or no structure influence
Group B	Soils with a strong mineralogical influence derived from clay minerals also commonly found in transported soils	(a) Montmorillonite (smectite group) (b) Other minerals
Group C	Soils with a strong mineralogical influence deriving from clay minerals only found in residual soils	(a) Allophane sub-group (b) Halloysite sub-group (c) Sesquioxide sub-group (gibbsite, goethite, haematite)

Table 30.9 Classification of residual soils
Data taken from Wesley and Irfan (1997)

It has to be recognised that there will be cross-linkages between the different categories; for example a material that is fresh rock (D = 1) but has no secondary cementing (C = 6) will not be a problematic material, even though the cementing category has a high score. Similarly, a residual soil (D = 6) that has hardpan cementing (D = 1) will not be problematic, as the cementing will overcome the decomposition due to weathering and result in a strong rock-like soil.

30.3.3 Characteristics and typical engineering properties

The stages of weathering result in different clay mineralogies, and these are reflected in the cation exchange capacity (CEC) of the clay fraction (Anon., 1990). Typical values are given in **Table 30.11**.

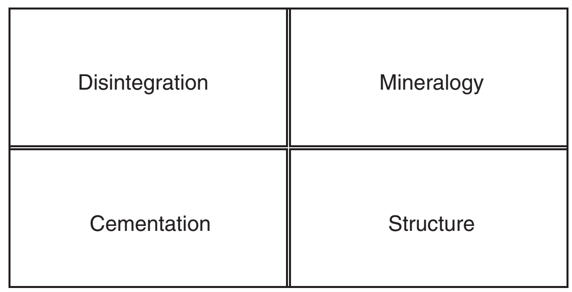

Figure 30.8 DMCS classification scheme

Grade	Disintegration	Grade	Mineralogy[1]
6	Residual soil	6	Smectite (vertisol)
5	Completely weathered	5	Smectite/kaolin (ferruginous)
4	Highly weathered	4	Allophane/halloysite (andosol)
3	Moderately weathered	3	Kaolinite (siallitic)
2	Slightly weathered	2	Kaolinite (ferrisol)
1	Fresh/faintly weathered	1	Kaolinite/gibbsite (ferrallitic)

Grade	Cementation[2]	Grade	Structure spacing
6	No cementing agents present	6	Very small (less than 60 mm)
5	No evident cementing effect	5	Small (60 mm to 200 mm)
4	Weakly cemented	4	Medium (200 mm to 600 mm)
3	Nodular	3	Large (600 mm to 2 m)
2	Honeycomb	2	Very large (greater than 2 m)
1	Hardpan	1	No evident macro-structure

[1] These are ranked in order of engineering behaviour rather than stages of weathering.

[2] This is a measure of secondary cementing of the weathered material, not the initial cementation of the parent rock.

Table 30.10 Proposed classification of tropical residual soils

Fersiallitic soils can comprise vertisols or andosols that form at the early stage of weathering. Vertisols commonly occur in areas of impeded drainage such as on valley floors. They are often black or dark brown in colour and contain smectite clay minerals. They often exhibit excessive shrinkage and swelling properties and present major engineering problems.

Andosols are fersiallitic soils that develop from volcanic parent rocks and contain amorphous allophane or halloysite. They frequently exist in an extremely loose state, and can have water contents of around 200%. Nevertheless, these high water contents do not reflect in their engineering behaviour since they generally have low compressibility and high angles of shearing resistance (Wesley 1973, 1977).

The latter stages of weathering (ferruginous, ferrisols, ferralitic) usually result in soils with red coloration, reflecting higher iron and aluminium sesquioxide contents. They generally contain low-activity kaolinite minerals, and do not usually present major engineering problems. However, they may perform quite differently from temperate sedimentary soils, and hence the application of standard classification systems can lead to difficulties.

Stage of weathering	Cation exchange capacity (mEq/100 g)
Fersiallitic soil	> 25 (typically 50)
Ferruginous soil	16–25
Ferrallitic soil	< 16

Table 30.11 Typical values for cation exchange capacity of the clay fraction
Data taken from Anon. (1990)

Ferruginous soils (red tropical soils) have red coloration but do not contain high iron oxide contents. Ferrisols (lateritic soils) have higher iron contents, and contain granular nodules (pisoliths) of iron cemented material. Ferricrete (laterite cuirasse or carapace) is an indurated deposit, heavily cemented with iron oxides, and can behave like weak rock.

The effect of secondary cementation is to improve the engineering properties. **Figure 30.9** shows the variation of void ratio, compressibility and strength properties (c' and ϕ') in a weathering profile. In the Grade VI residual soil, the void ratio will be high due to leaching out of minerals and the resulting structured form of the soil. This open structure results in high compressibility and low strength properties.

Figure 30.9 shows the effect that secondary cementing by sesquioxides (laterisation) can have on the residual soil near the ground surface. This results in an upper profile with variations in the degree of cementing, from a concretionary or partly cemented layer to a fully cemented layer at the surface. The presence of the sesquioxides partially fills voids and reduces

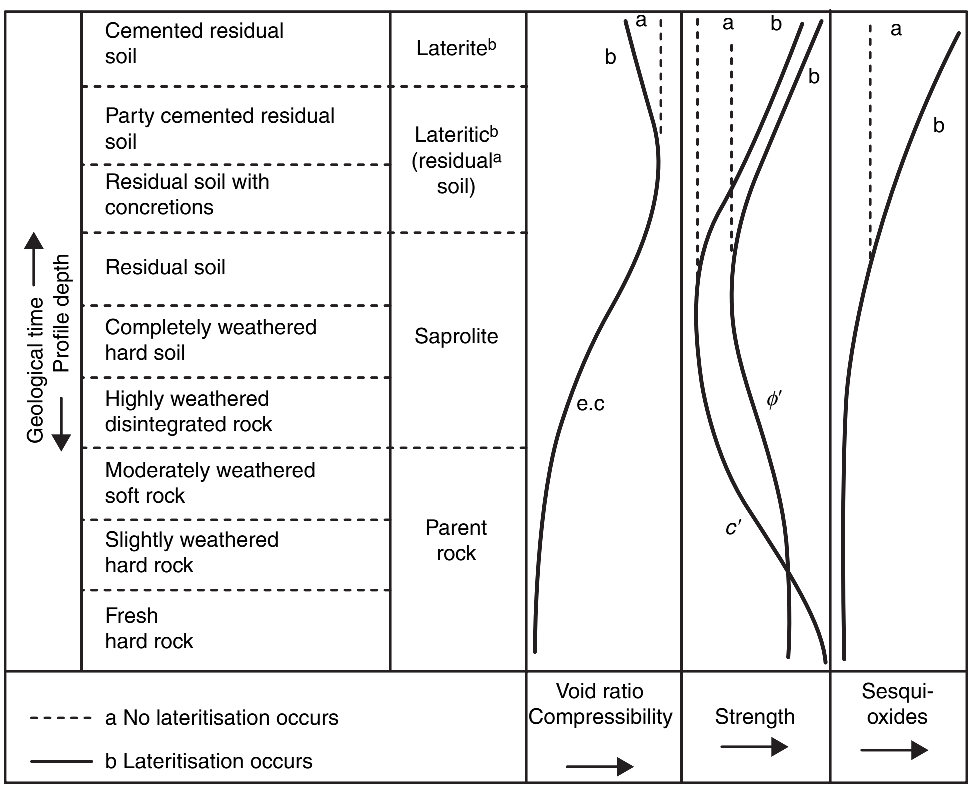

Figure 30.9 Changes in compressibility and strength in a weathering profile
Reproduced from Blight (1997), Taylor & Francis Group (adapted from Tuncer and Lohnes, 1977 and Sueoka, 1988)

the compressibility. Secondary cementing also produces major improvements in strength properties.

The permeability of tropical residual soils is controlled to a large extent by the macro-structure provided by relict joints etc. The more mature residual soils (Grade VI) may have lower permeability (**Table 30.12**), as the weathering will modify the macro-fabric and reduce the dominance of relict joints, as well as producing more clay minerals. However, materials that have been laterised can have higher permeability due to the open micro-structure and vesicular nature of the more cemented materials.

30.3.4 Problematic behaviour

Geotechnical classification schemes such as the Unified Soil Classification Scheme (USCS), which are widely used for temperate sedimentary soils, have severe limitations when applied to tropical soils. This gives tropical soils a reputation for being 'problematic' as they do not conform to these simple classification systems. However, many tropical soils, particularly the 'red' soils, can be good engineering materials and are often not problematic.

That is not to say that all tropical soils are problem-free. Some residual soils can exist in a loose state. Some ferruginous soils (Red Coffee soils) may exist with densities as low as 0.6 Mg/m^3, i.e. less than the density of water. This loose structure may be sustained by an unsaturated state, where suctions give strength to clay 'bridges', supporting the coarser particles and maintaining a low density. If the soil is wetted, so that the strength of the clay bridges is lost, the soil may collapse. Cementing agents may also maintain a loose metastable structure. If the soil is loaded beyond the yield strength of the bonding material, this can also lead to collapse. More information is provided in Chapter 32 *Collapsible soils*.

A further factor to be aware of is that the particles themselves may be crushable; this may be due to a loss of intrinsic strength as a result of chemical attack during weathering, or it may be that the coarse-grained size fraction is in fact made up of finer particles that are held together by secondary cementing or by a clay matrix. When subjected to high stresses the particles may start to crush, resulting in additional volumetric compressions (Lee and Coop, 1995).

Zone	Relative permeability
Organic topsoils	Medium to high
Mature residual soil and/or colluvium	Low (generally medium or high in lateritic soils if pores or cavities present)
Young residual or saprolitic soil	Medium
Saprolite	High
Weathered rock	Medium to High
Sound rock	Low to medium

Table 30.12 Permeability of weathering profiles in igneous and metamorphic rocks
Data taken from Deere and Patton (1971)

Another major problematic type of tropical soil is vertisols, as they contain smectite clays and can be highly expansive. Information on dealing with such swelling/shrinking soils is discussed in Chapter 33 *Expansive soils*.

Other problematic aspects of tropical soils are identified below. In many cases, the soils are not problematic *per se*, but problems result from inappropriate use of classification systems that were designed for temperate soils and are not applicable to tropical soils.

30.3.4.1 Presence of 'unusual' clay minerals

Some clay minerals found in tropical soils (halloysite and allophane) exist in non-platey forms. These are unlike the common clay minerals found in temperate soils (kaolinite, illite, montmorillonite), which are generally platey in nature. The engineering behaviour of allophanous or halloysitic soils is often very different from what would be predicted by schemes like the USCS (Wesley, 1973, 1977).

Allophane is amorphous (or is poorly structured) and can hold significant amounts of water within the amorphous mineral. On drying it appears that allophane forms a more ordered structure, completely changing the nature of the soil. An allophanous clay can change in behaviour to appear like a sand after drying.

Halloysite is a member of the kaolinite family but has a tubular habit. Water can be held within the 'tubes', where it does not contribute to the engineering behaviour. Halloysite exists in two forms: hydrated halloysite and metahalloysite containing no water of crystallisation. In metahalloysite the 'tubes' may split or become partially unrolled. The transition takes place if the moisture content reduces below about 10% or the relative humidity drops below about 40% (Newill, 1961). The change is irreversible.

Because of the ability of allophane and halloysite to hold water that does not contribute to the engineering behaviour, they are often classified as troublesome soils (since they have high natural water contents and liquid limits) (Wesley, 1973). However, they generally have very good engineering properties (Wesley, 1977). They show high angles of shearing resistance (compared to kaolinite or montmorillonite). Also, since they are not platey in form, they do not show a significant reduction in angle of shearing resistance due to clay particle alignment. Therefore, residual angles of shearing resistance are also high.

30.3.4.2 Presence of cementing agents

Many tropical soils are structured due to the presence of cementing agents that produce a physical bonding between soil particles. Schemes like the USCS are based on measurements on remoulded (or destructured) soil (Atterberg limits and particle size determination) and therefore cannot take account of soil structure. This is a severe limitation even for many temperate soils, but can be particularly limiting for tropical soils.

Under tropical weathering conditions iron and aluminium oxides are released and are not dissolved (as would occur in more acidic environments), so remain *in situ*. The presence of iron and aluminium oxides significantly affects the behaviour of tropical soils. Newill (1961) demonstrated that these oxides can suppress the plasticity of tropical clay soils, since on removal of the iron oxides the liquid limit was found to increase. This is the case if the oxides have an aggregating effect on the clay minerals. However, it is also possible for the oxides to contribute to plasticity, as was found by Townsend *et al.* (1971). If the oxides are present as amorphous colloids they can have a large water retention capability due to their large specific surface, and will then contribute to plasticity.

30.3.4.3 Difficulties in determining Atterberg limits

Atterberg limit determinations on tropical soils are sensitive to the methods of preparation (e.g. Moh and Mazhar, 1969). Different degrees of pre-test drying (e.g. oven dried, air dried or tested from natural moisture content) can produce very significant differences in the Atterberg limits (Anon., 1990; Fookes, 1997). In addition the amount of mixing of the soil during test preparation can also change the index properties significantly (Newill, 1961).

A comparison of the effects of different degrees of pre-test drying on the Atterberg limits is shown in **Table 30.13**. It should be noted that these changes are irreversible, and a permanent change in plasticity is produced by drying. To overcome problems relating to pre-test preparation, Charman (1988) suggests a procedure for testing the susceptibility to the method of preparation. This involves testing at different drying temperatures and different periods of mixing. If sufficient time is not available for such a detailed test programme, the best solution is to test the material without drying below the natural moisture content with a standard mixing time of five minutes.

30.3.4.4 Difficulties in determining particle size distributions

Like Atterberg limits, the measurement of clay content can also be affected by pre-test drying, since the drying process causes the clay particles to aggregate (Newill, 1961). These aggregations are only partially disaggregated by standard dispersion techniques, and clay fractions are often underestimated. For example, a red clay from Sasumua, Kenya showed a clay fraction of 79% when testing at natural moisture content, but this reduced to an apparent value of 47% after oven drying (Terzaghi, 1958). Another problem is that the coarse fraction of red soils often consists of weakly cemented particles which readily break down and change grading during sieving or compaction (Gidigasu, 1972; Omotosho and Akinmusuru, 1992).

30.3.4.5 Unsaturated state

Many tropical soils exist in an unsaturated state, since evapotranspiration is greater than precipitation. Water tables are often greater than 5 m deep, in many cases considerably deeper. The strength of these soils will be very dependent on moisture conditions.

Soil suction is made up of two components: *matric suction* and *osmotic suction* (also called *solute suction*). The sum is known as the *total suction*. Matric suction is due to surface tension forces at the interfaces (menisci) between the water and the gas (usually air) phases present in unsaturated soils (the surface tension effect is sometimes referred to as capillarity). Osmotic suctions are due to the presence of dissolved salts within the pore water.

In much of the soil science literature, suction is expressed in pF units, i.e. the logarithm (to base 10) of the suction expressed in centimetres of water (Schofield, 1935). For engineering applications, it is generally more convenient to use conventional stress units. The relationship to convert from pF units to kPa is given by:

$$\text{suction (kPa)} = 9.81 \times 10^{\text{pF}-2}. \quad (30.1)$$

The suction scale (showing both kPa and pF units) with some points of reference and indications of the moisture condition of a soil are shown in **Figure 30.10**.

The maximum suction that can be sustained within the pores of a soil will depend on the pore size. In a clean sandy soil, where pore sizes will be of the order of 0.1 mm or larger, the maximum suctions will be very small (typically < 5 kPa). In clean silty materials, where pore sizes might be of the order of 0.01 mm, the maximum suctions are likely to be less than 100 kPa. However, in clayey soils, where pore sizes can be less than 0.001 mm, high suctions greater than 1000 kPa can be sustained. This explains why clean sandy soils have no strength when they dry out (they lose the suction 'bonds' that hold them together as they cannot sustain high suctions). However, clayey soils can become very strong when they dry out, due to the high suctions that are maintained in the fine pores of the soil. The suctions pull the soil particles together and give the soil considerable strength in a dry state.

	At natural moisture content			Air dried			Oven dried (105°C)		
Location	LL	PL	PI	LL	PL	PI	LL	PL	PI
Costa Rica	81	29	52				56	19	37
Dominica	93	56	37	71	43	28			
Kenya (red clay)	101	70	31	77	61	16	65	47	18
Kenya (lateritic gravel)	56	26	30	46	26	20	39	25	14

Table 30.13 Effect of drying on classification tests on red soils

Suction (kPa)	Suction (pF)	Reference points	Moisture condition
1 000 000	7	Oven dry	
100 000	6		Dry
10 000	5		
1 000	4	Wilting point for plants Plastic limit	Moist
100	3		
10	2		
1	1		Wet
0.1	0	Liquid limit saturated	

Figure 30.10 The suction scale

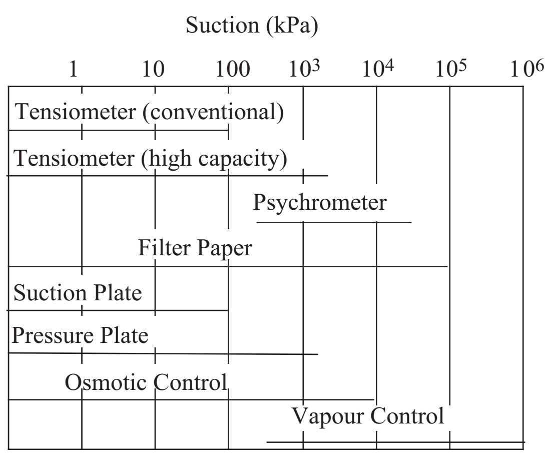

Figure 30.11 Ranges for which suction measuring/controlling devices are suitable

There are a number of different techniques for suction measurement and control. Their suitability varies according to the range of suctions operating. An indication of appropriate ranges is shown in **Figure 30.11**. It is generally necessary to use a variety of techniques in order to cover the entire suction scale.

As a soil dries out (or wets up) the suction within the soil will change. The relationship between water content and suction is known as the soil water retention curve (SWRC) (also called the soil water characteristic curve, SWCC). Although water contents

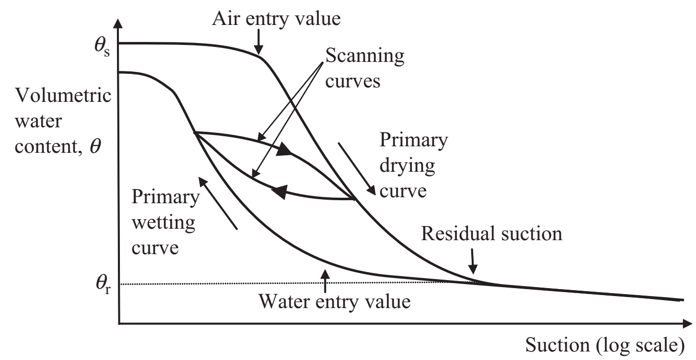

Figure 30.12 Typical soil water retention curve

are usually defined gravimetrically (i.e. by weight) in geotechnical engineering, soil water retention curves are often expressed in terms of volumetric water content, θ, or degree of saturation, S_r versus suction. **Figure 30.12** shows a typical SWRC.

If the soil starts from a saturated state and is then subject to drying, it will follow the *primary drying curve*. At a value of suction known as the *residual suction* (with a corresponding residual water content, θ_r) the SWRC may flatten, and much smaller changes in volumetric water content result from an increase in suction. To achieve zero water content (equivalent to an oven-dried condition) requires a suction of the order of 1 GPa (pF 7) (Fredlund and Xing, 1994). On wetting from an oven-dried state, the soil will follow the *primary wetting curve*. The primary drying and wetting curves define an envelope of possible states within which the soil can exist. If drying is halted part way down the primary drying curve and wetting is started, the soil will follow an intermediate *scanning curve*, which is flatter than the primary wetting curve, until the primary wetting curve is reached. Therefore, different suctions can exist at a given water content depending on the pathway followed.

The most commonly used approach to interpreting shear strength behaviour in unsaturated soils is to adopt an extended version of the traditional Mohr–Coulomb approach. This extension to unsaturated soils was put forward by Fredlund *et al.* (1978). It involves two separate angles of shearing resistance, to represent the contribution to strength from the net stress (total stress referenced to the pore air pressure) and matric suction (the pore water pressure referenced to the pore air pressure), giving the shear strength equation as

$$\tau = c' + (\sigma - u_a) \tan \phi^a + (u_a - u_w) \tan \phi^b, \qquad (30.2)$$

where

τ is shear strength;

c' is the effective cohesion intercept (many tropical soils demonstrate a true cohesion intercept at zero effective stress due to their bonded structure);

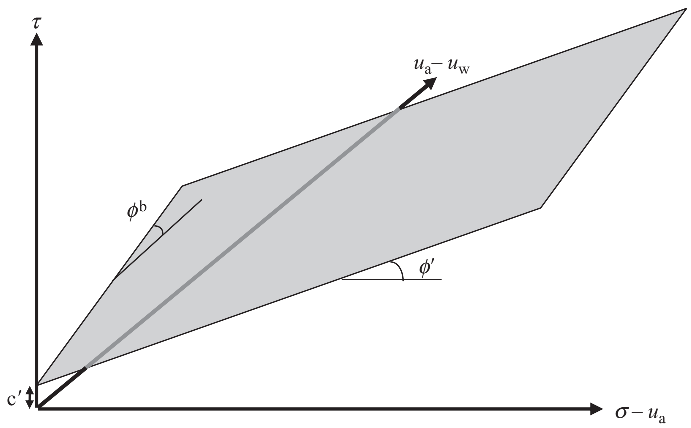

Figure 30.13 The extended Mohr–Coulomb failure envelope

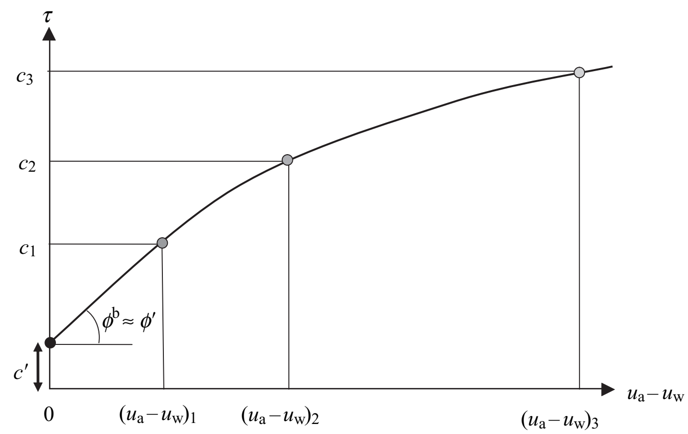

Figure 30.15 The extended Mohr–Coulomb failure envelope in matric suction space

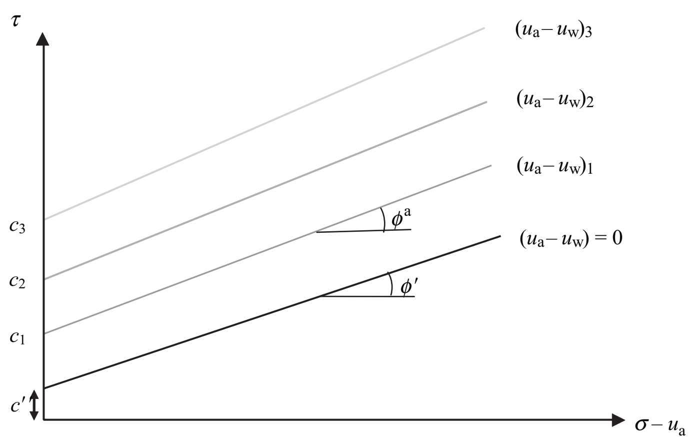

Figure 30.14 The extended Mohr–Coulomb failure envelope in net stress space

ϕ^a is the angle of shearing resistance for changes in net stress $(\sigma - u_a)$;

ϕ^b is the angle of shearing resistance for changes in matrix suction $(u_a - u_w)$.

This separates the effects of net stress $(\sigma - u_a)$ and suction $(u_a - u_w)$ and treats them differently by having two angles of shearing resistance relating to the two components of stress. The extended Mohr–Coulomb failure surface is shown in three dimensions in **Figure 30.13**. The surface is shown by views in the net stress plane in **Figure 30.14** and in the suction plane in **Figure 30.15**.

Figure 30.14 shows that the strength envelope increases as the suction increases. This can be represented as an increase in the total cohesion, *c* where:

$$c = c' + (u_a - u_w) \tan\phi^b \qquad (30.3)$$

Figure 30.15 shows the increase in total cohesion, *c*, as the suction increases. The slope of the graph is defined by ϕ^b. The relationship between τ and $(u_a - u_w)$ has been found to be non-linear by Escario and Saez (1986) and Fredlund *et al*. (1987). Below the air entry value (when the soil remains saturated) ϕ^b is equal to ϕ', but at higher suctions the value of ϕ^b reduces (**Figure 30.15**). The tangent value may fall to zero at high suctions, implying no further increase in strength at higher suctions.

A more complete model of unsaturated soil behaviour is that proposed by Alonso *et al.* (1990) and now known as the Barcelona Basic Model. This extends the Modified Cam Clay model to the unsaturated state, and provides the coupling between volumetric and deviatoric behaviour that is essential for a complete understanding of soil behaviour. It introduces the concept of a loading-collapse (LC) surface that defines yielding due either to external loading (total stresses) or wetting (loss of suction).

If the role of suction in an unsaturated soil is not recognised, then test results can be incorrectly interpreted. For instance, the compressibility of an unsaturated soil may be observed to be low at the water content at which the specimen is tested, as a result of the presence of a significant suction. However, the same soil could have much higher compressibility if the soil is wetted and loses the suction. Similarly, an apparent cohesion intercept observed in strength tests may be largely due to suction rather than being a true ‘cohesive’ contribution to strength from bonding. Again, this component of strength will reduce (and may even be lost entirely) if the soil is wetted.

30.3.5 Foundations

Problems with shallow foundations on tropical residual soils are usually associated either with collapse problems on loose, metastable soils or shrink–swell movements on expansive vertisols.

Collapse settlements can result from overstressing the cemented micro-structure of tropical soils. The compressibility may be low if the stresses applied do not exceed the yield strength of the cementing material. However, if the foundation is loaded beyond this stress, large and rapid settlements can take place.

Collapse settlements of foundations can also occur due to wetting. Some ferruginous soils (Red Coffee soils) may exist with densities as low as 0.6 Mg/m^3, i.e. less than the density of water. This loose structure is often maintained by bridges of clay minerals which support the sand- or silt-sized particles. The strength of these bridges is controlled by suction, and if the soil wets up or becomes flooded, there is a rapid collapse of the loose structure, resulting in large surface settlements.

A build-up in moisture under a pad or raft foundation can occur due to cutting off evaporation and changes in the temperature regime due to construction of a covered area (e.g. a concrete foundation). However, wetting up can also be caused by simpler means, such as the construction of soakaways for buildings, or leaking services, resulting in loss of strength and failure of the foundation.

If shallow foundations are constructed on vertisols, the likely problem will be seasonal movements as water contents change beneath the foundation due to wetting and drying. Foundation heave will be observed in wet season conditions, and settlements will be induced by shrinkage in dry season conditions. The zone of variation of water content will affect the edges of the foundation, while the central area of a large raft may not be affected. This results in differential movements that can be severely deleterious to the foundation and the overlying structure.

Methods to deal with foundation construction on expansive soils are:

30.3.5.1 Removal and replacement

Remove expansive material and replace with non-expansive soils. Generally the expansive layer extends to depths too great to economically allow complete removal and replacement. It must then be determined what depth of excavation and fill will be necessary to prevent excessive heave.

30.3.5.2 Remoulding and compaction

The swell potential of expansive soils can be reduced by decreasing the dry density. Compaction at low densities and at water contents wet of optimum will reduce the swell potential. However, the bearing capacity of the soil at the lower density may not be adequate. Some soils have such a high potential for volume change that compaction control does not significantly reduce swell potential.

30.3.5.3 Surcharge loading

If the surcharge load applied is greater than the swelling pressure then heave can be prevented. For example, a swell pressure of 25 kPa can be controlled by 1.5 m of fill and a concrete foundation. However, swelling pressures are often too high (~400 kPa) for this to be a realistic option.

30.3.5.4 Pre-wetting

This is based on the assumption that increasing the water content will cause heave prior to construction. If the high water content is maintained, there will be no appreciable volume change to damage the structure. However, the procedure has many drawbacks. Expansive soils are normally clays with low permeability, and the time required for adequate wetting may be years. Also, the increase in water content will reduce the strength of the soil and cause reductions in bearing capacity.

30.3.5.5 Moisture control by horizontal and vertical barriers

Soil expansion problems are primarily the result of fluctuations in water content. Non-uniform heave is the major cause of damage, as opposed to total heave. If changes in water content can be made to occur slowly and if the water content distribution can be made uniform, differential heave can be minimised. Moisture barriers do not prevent the heave taking place but have the effect of slowing the rate of heave and providing a more uniform moisture distribution.

Horizontal barriers installed around a building can limit the migration of moisture into the covered area. Concrete aprons, or paved areas for car parking can achieve this. The width of the barrier should be sufficient to extend the ‘edge distance’, i.e. the distance measured inward from the slab edge over which the soil moisture varies enough to cause soil movement (Post-Tensioning Institute, 1980).

30.3.6 Slopes

Many of the landslides which occur in the saprolitic zone of tropical residual soils are directly or indirectly controlled by relict discontinuities (Brand, 1985; Nieble *et al.*, 1985; Dobie, 1987; Irfan *et al.*, 1987; Irfan and Woods, 1988). Many types of mineral infillings and coatings may be present along relict discontinuities as a result of weathering processes, including clay minerals. Some discontinuities may be polished or slickensided as a result of internal deformation in the slopes (Irfan, 1998). These infilled or polished surfaces may have low residual angles of shearing resistance, providing a plane of weakness, so that failure is constrained to occur on these relict surfaces.

Landslides are often triggered by rainfall, particularly in tropical climatic regions, where rain storms can be very intense. Major landslides occur all too often, but minor landslides occur even more frequently. Although minor landslides may not lead to loss of human life, they still have economic and social impact.

A clear linkage has been established between landslide occurrence and high rainfall in tropical regions of the world. This has been confirmed by studies in Brazil (Wolle and Hachich, 1989), Puerto Rico (Sowers, 1971), Fiji (Vaughan, 1985b), Hong Kong (Brand, 1984; Au, 1998), Japan (Yoshida *et al.*, 1991), Nigeria (Adegoke-Anthony and Agada, 1982), Papua New Guinea (Murray and Olsen, 1988), Singapore (Pitts, 1985; Tan *et al.*, 1987; Chatterjea, 1994; Rahardjo *et al.*, 1998; Toll, 2001), South Africa (van Schalkwyk and Thomas, 1991) and Thailand (Jotisankasa *et al.*, 2008).

Soil slopes in tropical regions are normally unsaturated during the dry season, and the groundwater table may often be at depths of more than 10 m for most of the year. When the soil is unsaturated, suction or negative pore water pressure provides additional strength to the soil, hence stabilising the slope. This additional strength may disappear during an intense rainstorm when the soil becomes saturated and pore water pressure becomes zero.

Figure 30.16 shows rainfall data for a large number of landslides in Singapore (Toll, 2001). It shows the rainfall on the day of the landslide (*triggering* rainfall) plotted against the rainfall in the five-day period preceding it (*antecedent* rainfall). It can be seen that it is usually not a single rain storm that produces failure; rather it is a build-up of pore water pressure over a number of days due to the antecedent rainfall followed by a storm that finally triggers the landslide event. However, there are occasions where a single storm is big enough to produce a failure even when there has been no significant antecedent rainfall in the preceding days.

It is important when studying climate effects on slopes that we do not always assume that rainfall will produce a rise in water table level. Infiltration of rainfall at the surface can produce significant changes in pore water pressure without a change in water table (although a perched water table may be induced at the surface) (Toll, 2006).

30.3.7 Highways

Traditionally, materials used in the construction of road bases have been clean graded aggregates, generally obtained from crushed rock. However, in tropical climatic zones, good quality rock for crushing is often unavailable because of the extensive weathering that occurs in the tropics. Even when it is available, the costs of processing and transporting the material can make this an uneconomical option. Therefore naturally occurring materials such as lateritic gravels or calcretes are widely used for construction of roads with low traffic volumes. These natural materials generally contain a greater amount of fines, and the fines have higher plasticity, than is accepted by many existing specifications for construction materials. Details of materials which have been successfully used as road base construction materials in the tropics are given by Lionjanga *et al*. (1987), Grace and Toll (1989), Gidigasu (1991), Metcalf (1991), Netterberg (1994) and Gourley and Greening (1997).

Because naturally occurring gravels have greater quantities of fines it means that soil suction and fabric are major factors controlling their behaviour. The presence of around 10% clay in a lateritic gravel was sufficient to provide a matrix with small pore sizes which could sustain significant suctions (Toll, 1991). Yong *et al.* (1982) similarly report that a small clay fraction had an important effect in influencing the suction characteristics of a weathered granite. Therefore, the effects of suction should not be overlooked in granular materials if they contain small amounts of clay. Provided the fines are well distributed, it will be possible to develop high suction throughout the soil. The matrix of fines will then act as a binder which can hold the granular material together, thus imparting overall high strength and stiffness.

The ability to maintain soil suction, and hence maintain good performance, is highly dependent on the avoidance of wetting up of the road base material, particularly in unsurfaced roads. In cases where the water table is close to the surface, the benefits of suction cannot be relied upon, and conventional specifications using good quality aggregates must be adopted. For cases where the water table is more than 5 m below the

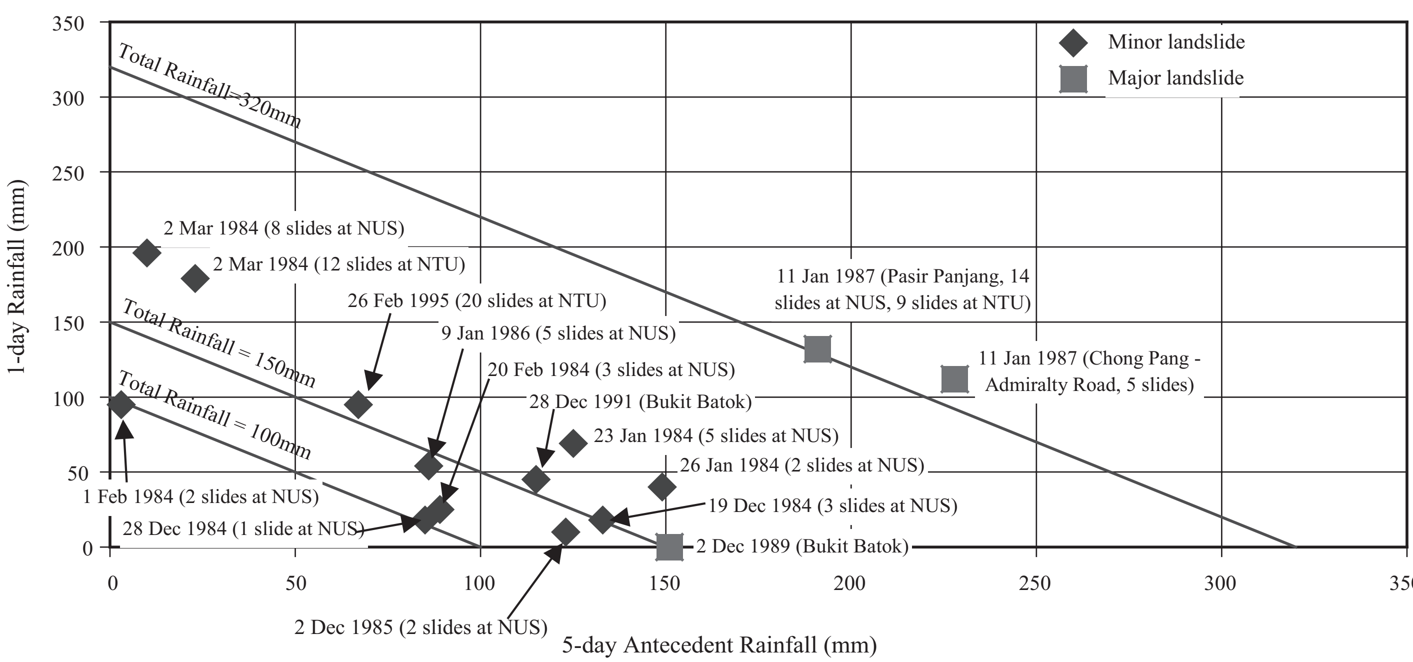

Figure 30.16 Rainfall events leading to landslides in Singapore

ground surface, reliance can be placed on suction, provided drainage measures ensure that water will not pond on the road surface. A bituminous surface is beneficial in preventing direct infiltration into the road base material.

Trial constructions in Kenya of low-volume roads surfaced with a sprayed bituminous seal coat compared lateritic gravel with conventional crushed stone for the road base (Grace and Toll, 1989). It was found that the lateritic gravel sections showed better performance. This was because failures of the bituminous surface coat allowed water to penetrate and spread within the high-permeability crushed stone base, softening the sub-grade and causing large areas of cracking. On the laterite sections, a small pothole formed where the bituminous surface coat failed, but it did not spread, due to the low permeability of the road base material. Any water accumulating in the pothole during a rain storm evaporated during drying periods. Therefore, the laterite sections performed better than the 'higher quality' construction methods.

Toll (1991) argues that a good material for a road base in a sub-tropical or tropical climate will have sufficient fines to allow significant suctions to develop and also produce low permeability. A small amount of clay can be beneficial in this. However, the fines content should not be so great as to suppress the dilatent tendency of the granular fraction or to significantly reduce the angle of shearing resistance. Also, any clay present should have low activity in order to restrict shrinkage and swelling. The fines should be well distributed throughout the fabric if they are to support high suctions and provide a strong binder, holding the granular fraction together. This also produces low permeability.

Charman (1988) provides comparisons between specifications for natural gravels for road bases used around the world. More recently, Paige-Green (2007) gives recommended material specifications for unsealed rural roads (**Table 30.14**) based on experience in southern Africa. This is based on distinguishing between materials that will become slippery, erode, ravel or form corrugations (**Figure 30.17**).

Paige-Green suggests a minimum value of soaked CBR (at 95% modified AASHTO compaction) of 15%. This is even lower than the *minimum* value of 20% suggested by Grace (1991) for bituminous sealed roads, combined with an *average* value of soaked CBR of 40%. Gourley and Greening (1997) suggest a minimum soaked CBR of 45% (at 100% modified AASHTO compaction) for sealed roads carrying less than 0.01 million equivalent standard axles (ESA), but a higher requirement of 55–80% for more highly trafficked roads carrying 0.5 million ESAs (the lower limit for road base CBR of 55% is for a weak sub-grade with CBR = 3–4% and the higher limit of 80% for a strong sub-grade with CBR > 30%).

30.4 Concluding remarks

Tropical soils pose many challenges for geotechnical engineers. They are highly structured at both micro and macro levels. They are often cemented due to deposition of minerals either during or after weathering has taken place. They can be highly heterogeneous. A major difficulty is that traditional classification systems that have been developed for temperate sedimentary soils cannot be used to infer likely engineering behaviour for tropical soils. Simple classification tests, such as Atterberg limits, cannot be easily determined, due to the presence of unusual clay minerals, such as halloysite and allophone, or due to the effects of iron or aluminium sesquioxides.

Tropical soils are often thought of as problematic soils, largely due to the difficulty in classifying them. However, many tropical soils, particularly the 'red' soils, often have good engineering properties, such as low compressibility and high strength. The cemented structure can enhance their strength.

Nevertheless, some tropical soils do demonstrate problematic behaviour. Examples are those that exist in a loose, metastable state that can collapse when loaded, or when subject to wetting. Other problematic tropical soils are vertisols that contain active smectite clay minerals that demonstrate excessive shrink–swell behaviour when subject to drying and wetting.

Property	Value
Maximum size (mm)	37.5
Maximum oversize index (I_o)[1]	5%
Shrinkage product (S_p)[2]	100–365 (maximum of 240 preferable)
Grading coefficient (G_c)[3]	16–34
Soaked CBR (at 95% modified AASHTO compaction)	> 15%
Treton impact value (%)	20–65

[(1)] I_o, the oversize index, is the percentage retained on 37.5 mm sieve
[(2)] S_p = linear shrinkage × (% passing 0.425 mm sieve)
[(3)] G_c = ((% passing 26.5 mm – % passing 2.0 mm) × (% passing 4.75 mm))/100

Table 30.14 Recommended material specifications for unsealed rural roads
Data taken from Paige-Green (2007) © The Geological Society

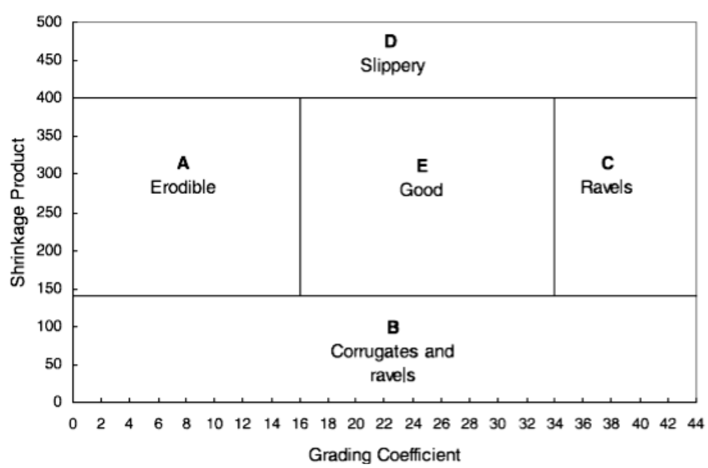

Figure 30.17 Categories of road performance for rural unsurfaced roads (See Table 30.14 for definitions of shrinkage product and grading coefficient)
Reproduced from Paige-Green (2007)

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30.5.1 Further reading

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Huat, B. B. K. and Toll, D. G. (2012). *Handbook of Tropical Residual Soil Engineering*. London: Taylor & Francis.

It is recommended this chapter is read in conjunction with

- Chapter 7 *Geotechnical risks and their context for the whole project*
- Chapter 40 *The ground as a hazard*
- Chapter 76 *Issues for pavement design*

All chapters in this book rely on the guidance in Sections 1 *Context* and 2 *Fundamental principles.* A sound knowledge of ground investigation is required for all geotechnical works, as set out in Section 4 *Site investigation.*