1. Introduction

1.1. The Working Party

The Working Party was convened in late 1985 by the Engineering Group of the Geological Society. The Treasurer of the Working Party, and also at that time Chairman of the Engineering Group, was Dr Roy Taylor of Durham University, who sadly died in the Autumn of 1987 when the Working Party was preparing for the public discussion of its first draft. This took place at the Geological Society, London on 8 March 1988. Dr Taylor was replaced on the Committee by Mr John Charman and it is due to his hard work that the financial and technical work continued. A particular debt of gratitude is owed to both members.

Tropical residual soils differ from transported soils which are principally derived from coastal, alluvial, wind blown or glacial processes. In the tropics, residual soils probably form the largest group with which the engineer has to deal. Being formed in situ these soils have particular characteristics which distinguish them from material deposited from a fluid medium such as wind or water.

Much has been written on the various tropical residual soils, in pedological, geological, geographical and engineering literature. However, from the engineering point of view, there is considerable confusion as to what defines a residual soil, how it is formed and what its properties are. It is reasonable to conclude that there is at present a considerable gap between scientific and engineering knowledge. Many engineers mistakenly call all red tropical residual soils 'laterite', whereas the original scientific description (Buchanan 1807) confines it to a fairly small group of red soils which harden irreversibly on exposure. This report generally avoids the use of the term 'laterite' except in its original Buchanan sense.

The aim of the Engineering Group of the Geological Society was to establish a reasonably comprehensive guide to the classification of tropical residual soils. The members of the Working Party were drawn from persons known to have been particularly concerned with tropical residual soils such as academics, researchers, contractors or consultants and included amongst their number geologists, geomorphologists, pedologists and civil engineers. Two members were given specific responsibility for drafting each of the various chapters, and other members of the Working Party cooperated with them according to their particular expertise. Discussions were held with various authorities outside the Working Party who had specific knowledge/expertise for a given chapter; they are listed in the acknowledgements. Various specialists with wide and extensive experience were sent the whole Draft Working Party Report for comment and again they are listed in the acknowledgements. Many others contributed in various ways and the public meeting in March 1988 produced helpful comments and ideas. To contributors and to others who may have been inadvertently omitted from the acknowledgements, thanks are due.

The Report is a team effort and, given the depth, breadth and diversity of the subject, may not be liked by all. However, it is hoped it will be of value, especially in the field and laboratory, to those practitioners who have perhaps only limited or partial knowledge of tropical residual soils. In particular, it is hoped that the Report summarizes the principles behind the formation of tropical residual soils, and that the classification system proposed will enable engineers and geologists to recognize such soils in the field. The classification system should also indicate that residual soils may contain ingredients or fabric which could give misleading results or could contribute to expensive delays during construction and/or inadequate performance during its working life.

The Engineering Group charged the Working Party with the overall task of providing a workable and practical classification of residual soils which was scientifically based and suitable for engineering use. The details were left to the Working Party but it was intended for civil engineers, engineering geologists and geomorphologists working on foundations, highways, tunnels, dams and hydro-schemes and other engineering projects in residual soils. The Working Party limited its geographical scope to residual soils developed in tropical and sub-tropical climatic environments but excluded relict tropical residual soils such as those in south west England which formed in tropical and sub-tropical climates but which no longer exist in the area. It was felt that the lower boundary of the residual soil should also be limited but this is more problematical and is discussed in Section 1.2. Transported tropical soils were also specifically excluded, although their relevance to engineering practice was recognized, as this would have widened the scope of the Report even further. Their inclusion would also have necessitated a consideration of the properties imparted to the transported soil by the transporting and depositing mechanisms. Duricrusts are included however, as they have grown in situ.

1.2. Tropical residual soils

The processes forming residual soils include incorporation of humus (decaying vegetation), physical and chemical weathering, leaching of insoluble materials, accumulation of insoluble residues, downward movement of fine particles (lessivage) and disturbance by root penetration, animal burrowing, free fall and desiccation. Acting individually or together, they produce a succession of more or less distinct horizons approximately parallel to the land surface which can be disconformable with the rock structure. The sequence of horizons at any one site constitutes the soil profile.

Soil layers close to the land surface are strongly influenced by humus, and seasonal and other cycles of wetting and drying. With increasing depth, there is an absence of organic matter and a reduction of seasonal moisture content fluctuations. At depth, water movement is slower, and solutes and fine particles are less easily transported through the soil profile. Consequently mineralogy and particle size distribution, and hence engineering properties, may change with depth even though the entire profile has developed from an originally uniform parent rock. Highly altered minerals in horizons near the surface (described in Chapter 2 as ferallitic) often pass downwards to less altered (fersiallitic) horizons, in which the original minerals of the rock are preserved largely unaltered, or as partly altered but still intact pseudomorphs. Clay contents often decline downward and 1:1 layer lattice minerals (e.g. kaolin) may change to 2:1 minerals (e.g. smectite), giving significantly different engineering characteristics. Material found at depth in a tropical soil profile may resemble 'grus' or eluvium found in higher latitudes over weathered rock. Iron segregations are typically found in the upper parts of the profile, although they may extend to depths of more than 10 m.

The lower limit of the soil/rock profile *for purposes of this Report* was subject to considerable discussion. Essentially there are four realistic possibilities, all of which may be visualised considering the sixfold weathering classification, Table 10 of BS 5930 (1981), which was developed from the first three Working Parties: Core Logging (1970), Engineering Geology Mapping (1972) and Rock Masses (1977).

The four possibilities considered were (see Table 1.1 and Fig. 1.1) as follows.

(1) To the base of weathering Grade VI. Although it is correct within the scope of the Working Party this was thought to be somewhat restrictive for engineering purposes as much material normally described as 'soil' occurs below this Grade in the weathered profile.

(2) The base of weathering Grade III, but considering the soil component only. This concept received considerable support but was rejected as it departed from the concept of residual soil in the spirit of the brief. In weathering Grades III and II, the rock mass becomes more and more important in controlling the engineering behaviour and the soil itself is less well developed as a component within the weathering profile.

(3) The base of weathering Grade III, but considering both soil and rock components. This was rejected for similar reasons to (2) above, i.e. the

TABLE 1.1. *Scale of weathering grades of rock mass*

Term	Description	Grade
Fresh	No visible sign of rock material weathering; perhaps a slight discoloration on major discontinuity surfaces.	I
Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discoloured by weathering.	II
Moderately weathered	Less than half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones.	III
Highly weathered	More than half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a discontinuous framework or as corestones.	IV
Completely weathered	All rock material is decomposed and or disintegrated to soil. The original mass structure is still largely intact.	V
Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.	VI

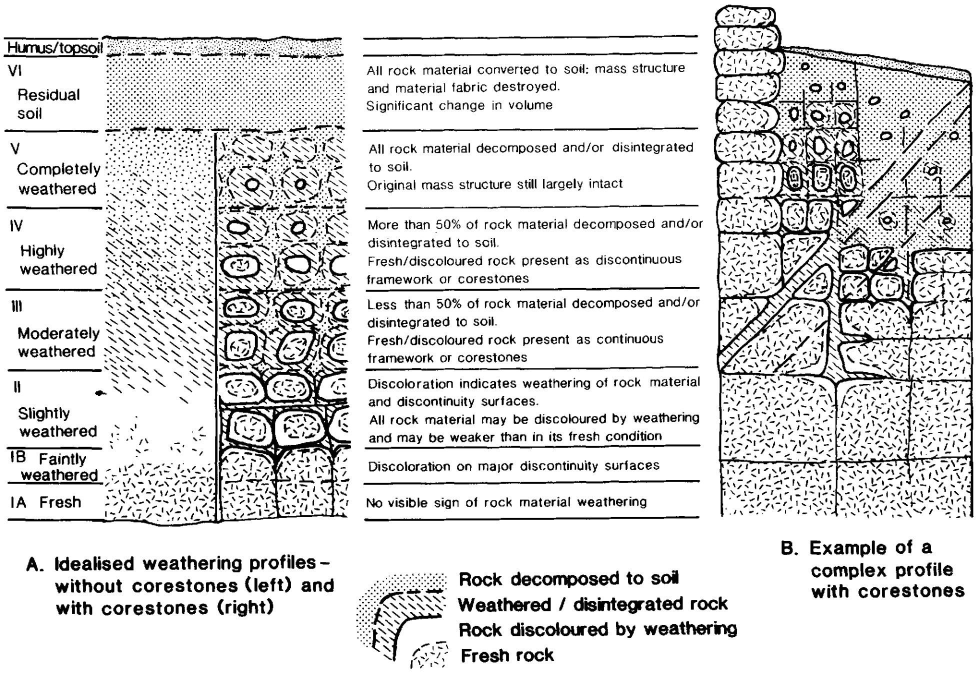

FIG. 1.1.

volume of soil within the profile was small relative to rock which increasingly controls mass behaviour.

(4) To the base of weathering Grade IV. This was the definition chosen for the base of the residual soil in this Report. It corresponds to the term 'Saprolite', i.e. weathered mantle, in common scientific and geographical soil use. It has the advantage of including most of the soil in the weathered profile of Table 1.1 and in the profile it occurs approximately where the mass and material properties are still 'soil-like'. Below, in weathering Grade III, rock-like characteristics begin to dominate both the mass and the material.

It must be emphasized that the definition of residual soil used by the Working Party, i.e. down to the base of weathering Grade IV, is arbitrary. In nature, many soil profiles are gradational in their characteristics. The fabric or structure developed and inherited plays an important part in the mass characteristics, especially from an engineering point of view. These vary from soil to soil and from location to location and it is of utmost importance to note that they must be assessed individually for each site from top to bottom of the profile.

1.3. Structure of the report: contents

The central theme of the Report is developed around the classification and description of tropical residual soils. Lengthy treatment of engineering characteristics and performance is neither the responsibility nor aim of the Report but they are given some consideration in order to demonstrate the relevance and objectives of the classification.

Chapter 2 discusses in some detail the origins, weathering processes and distribution of tropical residual soils. This chapter is intended to set the scientific scene as a basis for the field and practical engineering aspects which follow. Pedogenic factors influencing the characteristics of residual soils, including duricrusts, are discussed principally following the system of Duchaufour (1982). Factors influencing the depth of residual soil including regional, geological and geomorphological settings, weathering and erosion history are also presented.

Chapter 3 is concerned solely with classification. There have been many attempts to reconcile the characteristics of tropical soils with standard geotechnical classifications; none has been successful. This is largely because many of the special properties of the soils derive from the fact that they are of a weathered origin rather than the sedimentary origin more familiar to the engineer. The best developed scientific classifications are those of the pedologist; hence a pedological scientific classification has been adopted based on many sources, from which an engineering classification has been derived. It is hoped that once the engineer becomes familiar with the terms used, the extensive scientific data available from pedological and geomorphological sources may be more easily accessed. The basic divisions are duricrusts, vertisols, ferruginous soils, ferallitic soils and fersiallitic soils.

In Chapter 4 numerous tables are used to provide a framework of field descriptions of tropical residual soils compatible with the previous chapters. The field description is considered in three principal categories: general characteristics; soil material characteristics and soil mass characteristics. In addition, data collecting procedures and field activities are discussed, including in situ tests which may be carried out by hand.

In Chapter 5 sampling and testing is described in a conventional manner; emphasis being placed on those procedures and techniques which need to be modified from accepted or standard methods used with sedimentary soils. Chemical and mineralogical tests are included, together with in situ tests requiring equipment not normally carried by hand.

If conventional tests are made on some residual soils, it may be difficult to establish the usual relationships and correlations and local empirical relationships may have to be assessed from experience. In particular for many tropical residual soils the effect of drying or even partial drying at moderate temperatures is to produce changes in their physical behaviour. An alternative classification system based on void ratio is put forward.

Chapter 6 gives guidelines on engineering behaviour and characteristics. Confusion can occur if concepts and correlations derived from experience with sedimentary soils are used to predict the construction behaviour of residual soils. In particular the following properties and implications for engineering behaviour are considered: mineralogy, variable soil structure and the presence of bonding between the particles, variable void ratio, permeability, discontinuities of low strength, and partial saturation frequently present to considerable depth.

2. Origins and distribution of tropical residual soils

2.1. Tropical weathering

In tropical regions weathering of primary minerals is more intense and occurs to greater depths than elsewhere. Organic matter is rapidly degraded and rarely becomes incorporated below a thin surface layer. Consequently weathering occurs mainly by hydrolysis in near-neutral conditions at depths well below the influence of acidic organic decomposition products. The alteration is often so intense that the soil materials behave, in an engineering sense, quite differently from the parent materials from which they were derived. This is rarely true of the less altered soils of temperate regions.

Iron and aluminium oxides and hydrated oxides released by tropical subsurface weathering are not dissolved as much as in more acidic soil environments characterising temperate lands and consequently they tend to remain in situ. Iron oxide is crystallized as haematite (αFe_2O_3) when the soil is seasonally desiccated, or as goethite ($\alpha Fe_2O_3.H_2O$) in a constantly humid environment; haematite giving the soil a red colour, goethite a brown or ochreous colour. Gibbsite ($\gamma Al_2O_3.3H_2O$) is the main aluminium oxide formed.

Silica is lost in solution or combines with other weathering products to form 2:1 layer silicate clay minerals (mainly smectite), or more often silica-deficient 1:1 minerals (mainly kaolinite). Bases (K, Na, Ca, Mg) are either lost in solution or are incorporated into 2:1 minerals; kaolinite accommodates little or no bases. The 2:1 minerals may move down the profile as dispersed clay particles in suspension (lessivage or illuviation) to form clay-depleted upper horizons and clay-enriched lower horizons, but oxides and 1:1 minerals are less susceptible to this process.

2.2. Duricrusts

Hardened horizons form as a result of residual accumulation of iron and alumina or the precipitation of calcite, dolomite or gypsum. Transportation of ferrous iron in solution may occur over very short distances to give a mottled horizon with concretions or rusty segregations and pale, iron-depleted patches. Alternatively it may occur over greater lateral distances, the iron often being redeposited in the ferric (Fe^{3+}) form and accumulating on foot slopes and the floors of valleys and hollows.

The nomenclature for hardened (indurated) crusts remains confused (Goudie 1973). The term 'laterite' is widely used for ferruginous types, but has also been applied to soft, clay-rich horizons showing marked iron segregation or mottling and to loose gravelly materials comprising mainly iron oxide concretions or pisoliths (Prescott & Pendleton 1952; Alexander & Cady 1962; Sivarajasingham *et al.* 1962; Maignien 1966; McFarlane 1976; Young 1976; Schellmann 1981; Goudie & Pye 1983). According to McFarlane (1976) these non-indurated materials form links in a sequence of lateritic weathering, in favourable conditions leading to the development of a continuous sheet of indurated laterite forming a surface or near-surface duricrust.

When rich in iron, duricrusts may be called 'ferricrete'; those with a higher content of aluminium oxides are described as 'alucrete' or more commonly 'bauxite' (Bleackley 1964; Dury 1969; Aleva 1979; Valeton 1983). McFarlane (1983) concluded that 'the absolute chemical content has failed to provide definitions of laterite and bauxite and to distinguish between them'. The sesquioxide ratios in these deposits are variable and may not be related to the composition of the underlying rock. Conventionally alucrete is an appropriate term where Al_2O_3 exceeds 50 per cent, although bauxite has been used commercially for ores with smaller quantities of Al_2O_3.

The development of laterite or bauxite on isolated limestone substrates (e.g. coral atolls) usually results from weathering of far-travelled aeolian additions (volcanic ash or loess) which accumulated slowly over long periods of time.

Other types of duricrust (Goudie 1973) or pedocrete (Netterberg 1985) arise by re-precipitation of calcite (calcrete), dolomite (dolocrete) or gypsum (gypcrete) from solutions moving downwards or upwards through the soil profile. Soluble silica may be redeposited as silica gel instead of combining with bases to form clay. The resulting silcretes (Summerfield 1983) occur mainly at depth within well-drained soils formed from siliceous parent materials with little alumina, such as quartzose sandstones. Re-precipitation of silica is also favoured by warm humid conditions (Twidale & Hutton 1986), though with seasonal desiccation of the profile. However, accumulation is so slow that thick continuous silcretes are usually associated only with very old land surfaces, such as the Early Tertiary Cordillo Surface of South Australia (Wopfner 1978) and the African Surface of southern Africa (Partridge & Maud 1987). Silica may also be redeposited in porous strata deep in the earth's crust below the zone of pedogenesis. Where such diagenetic silcretes are exhumed by erosion they often remain on the surface, being much more resistant than the unsilicified deposits above and below them. Locally this may give the erroneous impression that they have been formed at the surface by pedogenic processes. For the same reason, pedogenic silcretes originating in lower parts of the landscape are often preserved on present-day summits and plateaux. Most silcretes have more than 60% SiO_2 content. Calcretes contain 60 to 97% $CaCO_3$, with a mean value of almost 80% (Goudie 1973).

Laterite and bauxite are the most widespread types of duricrust in tropical regions. Other types occur in special geochemical situations, not necessarily restricted to tropical climates.

2.3. Pedogenic factors and characteristics of residual soil types

There are a number of systems of classification available for the study of tropical soils (see Appendix to this chapter, p 21). However, this report follows Duchaufour (1982), ensuring that the scheme recommended is based firmly upon weathering and other processes of pedogenesis established by detailed analytical and experimental work. Table 2.1 gives approximate equivalents in other commonly used systems; more detailed subdivisions and their equivalents are given in Fig. 3.3. This system, which is based entirely upon an understanding of the pedogenic processes, highlights the compositional soil characteristics which influence engineering behaviour, e.g. mineralogical composition. It is therefore more relevant to engineering geology than those based on other, often ephemeral, criteria of more value in agriculture. The significance of the Duchaufour (French) classification system for engineering properties and behaviour is discussed further in Chapter 3.

Duchaufour (1982) distinguished three phases of residual soil development in tropical areas (Table 2.2). They are characterized by increasing weathering of primary minerals, increasing loss of silica and increasing dominance of new clay minerals formed from dissolved materials. Their generalized distribution is shown in Fig. 2.1. The phase represented by the soil profile at any particular site is determined by numerous factors including: the age of the land surface (how long the soil has been forming), the climate during this period of soil development (temperature, humidity and seasonal desiccation), the

TABLE 2.1. *Approximate equivalents of various major classes of tropical residual soils (for more detailed subdivision see the Appendix to Chapter 2)*

Duchaufour (1982)	FAO-UNESCO (FAO 1985)	USA (Soil Survey Staff 1975)
fersiallitic soils	cambisols, calcisols, luvisols, alisols	alfisols, inceptisols
andosols	andosols	inceptisols
ferruginous soils	luvisols, alisols, lixisols, plinthosols	alfisols, ultisols
ferrisols	nitosols, acrisols, lixisols, luvisols, plinthosols	ultisols, oxisols
ferrallitic soils	ferralsols, plinthosols	oxisols
vertisols	vertisols	vertisols
podzols	podzols	spodosols

TABLE 2.2. *Summary of residual soil phases (Duchaufour 1982) in relation to climatic factors*

Phase	Soil type	Zone	Mean annual temperature (°C)	Annual rainfall (m)	Dry season
1	fersiallitic	mediterranean, 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

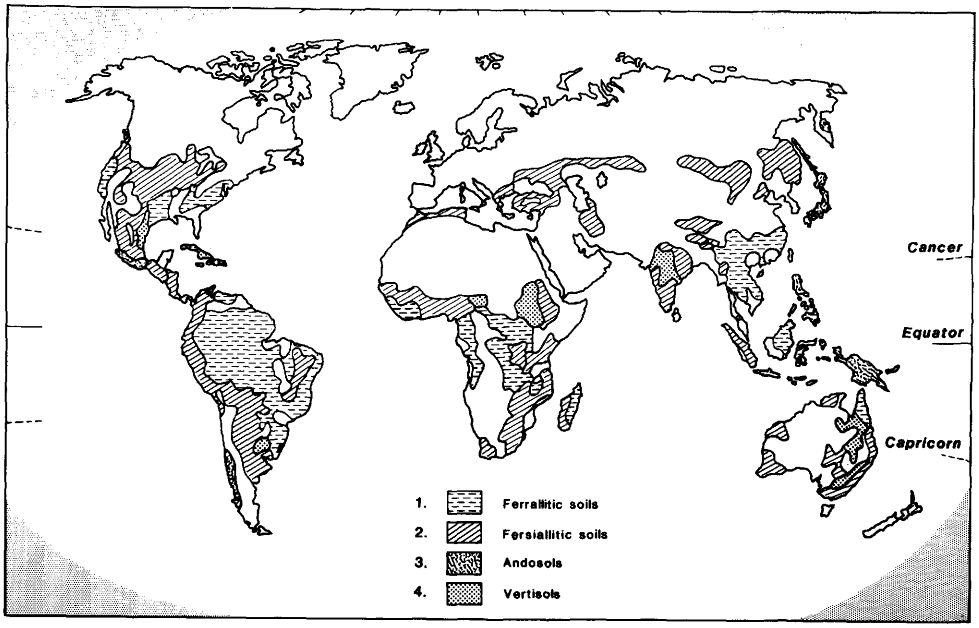

FIG. 2.1. Simplified world distribution of the principal types of tropical residual soils (based on F.A.O. World Soil Map). These broad classes of soils extend beyond the tropics in favourable circumstances, which include high rainfall sub-tropical, continental east coasts (ferrallitic soils), and the west coast/Mediterranean and continental interiors in mid latitudes (fersiallitic soils).

composition of the soil parent material (amounts of iron and base-rich primary minerals, of total silica and alumina), and topography (controlling lateral transportation of bases, silica and iron in solution, and rejuvenation of profiles by erosion on steeper slopes). Many features however are related to weathering in earlier periods and to different climatic conditions.

2.3.1. Phase 1: fersiallitic soils

Such soils probably form mainly in subtropical or Mediterranean climates, with mean temperatures of 13 to 20°C, rainfall 500 to 1000 mm, and a hot dry season; tropical sub-types are also known (Duchaufour 1982, p 378). Under subtropical and Mediterranean conditions, the upper soil horizons undergo decalcification and weathering of primary minerals during the wet season. The elements freed by these processes are largely retained in the profile as a result of capillary rise during the dry season and effective bioturbation of the soil (e.g. by termites). With limestones much of the dissolved calcium carbonate is re-precipitated in this way to form a thin discontinuous calcrete horizon in the subsoil. In regions with a dry season too long to allow a dense forest to develop, the calcareous crust becomes thick and continuous, especially on footslopes which periodically receive bicarbonate-rich water from upslope (Netterberg 1980).

Although weathering of primary minerals is more intense in tropical than temperate (siallitic) soils, it does not affect quartz, alkali felspars or muscovite. Because of the more intense weathering, fersiallitic soils contain more iron oxide than the Brunified (siallitic) soils of Duchaufour (1982) and the free iron is usually greater than 60% of the total iron content. The main new clay mineral formed is smectite, especially where drainage is impeded so that much of the silica and bases released by weathering are retained in the profile. However, kaolinite may appear on older well drained land surfaces and silica-poor parent materials, such as basalt. Where the parent material is clay-rich, the composition of the soil clays may be determined mainly by minerals derived with little alteration from the sediment. The 2:1 clays often undergo lessivage to form clay-enriched subsurface horizons, and some iron oxide may be carried down with the clay to form a red or red-mottled, clay-enriched B horizon. The clay fraction ($<2\,\mu m$) usually has an exchange capacity of about 50 mEq/100 g, but it may be as small as 25 mEq/100 g. Extremely quartzose rocks without iron or weatherable minerals do not produce fersiallitic soils in any topographic or climatic situation.

Silica and bases lost in solution may also move laterally and accumulate where drainage is impeded, for example on footslopes, valley floors and enclosed hollows. In such situations recombination with other weathering products to form swelling 2:1 clays often results in patches of clay-rich deposits. These crack in dry seasons and humic, weathered topsoil is incorporated into subsoil horizons by self-mulching to form vertisols (black cotton soils).

With recent volcanic ashes, fersiallitic soils are often associated on slopes with uniformly dark-coloured, very porous soils of low bulk density, known as andosols. These immature thixotropic soils owe their characteristics to the formation of complexes between humus and imperfectly crystallized aluminosilicates (allophanes) produced by rapid weathering of volcanic glass. As silica is lost during development of andosols, allophanes are replaced by disordered fibrous clay minerals (imogolites) and eventually by the globular or tubular 1:1 clay mineral halloysite (Dudas & Harward 1975).

2.3.2. Phase 2: ferruginous soils

These soils form in climatic zones which are either more humid (without a dry season) or slightly hotter than the Mediterranean areas where most fersiallitic soils originate. They tend to be somewhat more strongly weathered than the fersiallitic soils, but orthoclase and muscovite typically remain unaltered. Kaolinite is the dominant clay mineral; 2:1 minerals are subordinate and gibbsite is usually absent. The exchange capacity of the clay fraction is 16 to 25 mEq/100 g and is greatest in the clay enriched horizons because of preferential lessivage of 2:1 minerals.

On older land surfaces and the more permeable and base-rich parent materials, ferrisols transitional to phase 3 often occur. These have thicker profiles (often greater than 3 m) than typical ferruginous soils, the lower horizons being kaolinitic saprolite. At high altitudes under forests with tree ferns, their surface horizon is often humus-rich and very acid, leading to partial alteration of kaolinite to gibbsite in lower parts of the humus-rich horizon.

2.3.3. Phase 3: ferrallitic soils

Ferrallitic soils form in the hot, humid tropics (annual rainfall greater than 1500 mm, mean temperature >25°C, with little or no dry season), and have profiles several metres thick. All primary minerals except quartz are weathered by hydrolysis in the neutral conditions, and much of the silica and bases are removed in solution. Any remaining silica combines with alumina to form kaolinite, but usually there is an excess of alumina, which forms gibbsite. The exchange capacity of the clay fraction is less than 16 mEq/100 g, and usually there is no clay lessivage. Upper horizons of the profile are weakly acidified by organic decomposition products which cause dissolution, chelation and mobilization of iron and aluminium oxides, and decompose any kaolinite present to produce more gibbsite. Depending on the balance between iron and aluminium oxides, ferrallitic soils may be divided into ferrites, in which iron oxides dominate and which occur mainly over rocks low in aluminium, and allites in which aluminium oxides (usually gibbsite) predominate.

Although not included in the classification adopted for this Report, some local varieties occur. Over permeable quartz-rich substrates, high groundwater tables may induce podzolization leading to the removal of iron and aluminium in acid environments and the formation of residual 'white sand' (albic) horizons from 1 to 3 m thick. Typically the white sands are found on coastal plains where sandy sediments occur under high rainfall conditions. Similar materials are also present over acidic crystalline rocks and sandstones on the ancient plateaux of former Gondwanaland (Bleackley & Khan 1963; Heyligers 1963; Fairbridge & Finkl 1984). They also occur under savanna conditions where the precipitation is from 600 to 1000 mm, but here they may be relict features of previous (Pleistocene) periods of wetter climate.

Although most ferrallitic soils probably take 10^4 or more years to form, development is more rapid on silica-poor rocks such as basalt than on silica-rich parent materials like granite or quartz-rich sediments. The greater silica content of quartzose parent materials is often reflected also in the presence of kaolinite in the subsoil horizons formed by neutral hydrolysis. This zone of kaolinite formation is often poorly drained and coarsely mottled with white, red and ochreous patches; it may be overlain by a 'lateritic' horizon enriched with iron mobilized from acidic near-surface horizons or by changes in the position of the water table. Formation of kaolinite is encouraged by the poor drainage, whereas free drainage removes dissolved silica more rapidly and favours development of gibbsite. The iron-enriched horizon may be moderately or strongly indurated, pisolitic from welding of concretions, or vesicular from precipitation of iron in a polyhedral network of fissures and subsequent removal of the softer material between the fissures.

The only climate suitable for formation of ferrallitic soils is the very hot, humid environment of the tropical evergreen rainforest. Where similar soils extend into drier climatic zones, it is probably the result of climatic shifts during the Quaternary. Conversely, some residual soils in areas currently favourable to ferrallitization are only at the fersiallitic or ferruginous stage (phase 1 or phase 2); this is either because they have been rejuvenated by erosion on slopes, or because they are formed on recent deposits which have not been exposed to the tropical rainforest environment for long.

The fabric and other characteristics of soils formed in each of the three phases of weathering are discussed in Chapter 3.

2.4. Factors influencing depth of residual soil mantles

Ability to predict the depth of residual soils is limited by complex interactions of several controlling factors. Nevertheless some guidelines are possible. Variability may be defined as zonal, regional or local. Within characteristic climatic zones it is possible to indicate likely ranges of weathering depths. Figure 2.2 (from Strakhov 1967) shows that strongly altered surface horizons in the tropics give way at depth to less altered materials which are often similar to the near-surface horizons of profiles in cooler and less humid climatic zones (Fig. 2.3). Weathered materials and deep profiles inherited from past periods often complicate this picture. Consequently it is more useful to concentrate upon regional and local conditions where the following factors should provide a logical framework to assist understanding in the field.

2.4.1. Location of the field site

This is an important factor; the site may be considered in terms of regional climate and structural province at one extreme, and of outcrop geology, local structure and site morphology at the other. At the regional scale, this is part of a desk study, but at the local scale it depends on an appreciation of the specific properties of the site and its surroundings. Modern climatic factors of importance include mean annual temperature, annual rainfall and its seasonal distribution. As most soils are developed over long periods, past Quaternary climatic fluctuations are important; with extremely old soils even latitudinal changes resulting from plate movements may be relevant.

2.4.2. Geological development of the site

This influences depth of the weathered mantle through tectonic history. Intersection of faults or joint sets often creates basinal areas of deep weathering, especially in granites with near orthogonal sets of fractures, though basins, domes and troughs in the basal weathering front are common on all crystalline rocks, usually as a result of fracture zones or faults.

Folded supracrustal rocks, such as greenstone belts, often have thick laterites over metavolcanics and ironstones, where deep weathering may reach 100 m or more (Gaskin 1975). Where such formations have steep (near vertical) foliation, weathering may penetrate to several hundred metres.

Sedimentary rocks in humid tropical regions can weather to a thick, friable ferrallitic soil, which is often subject to rapid sheet erosion, gullying and mass

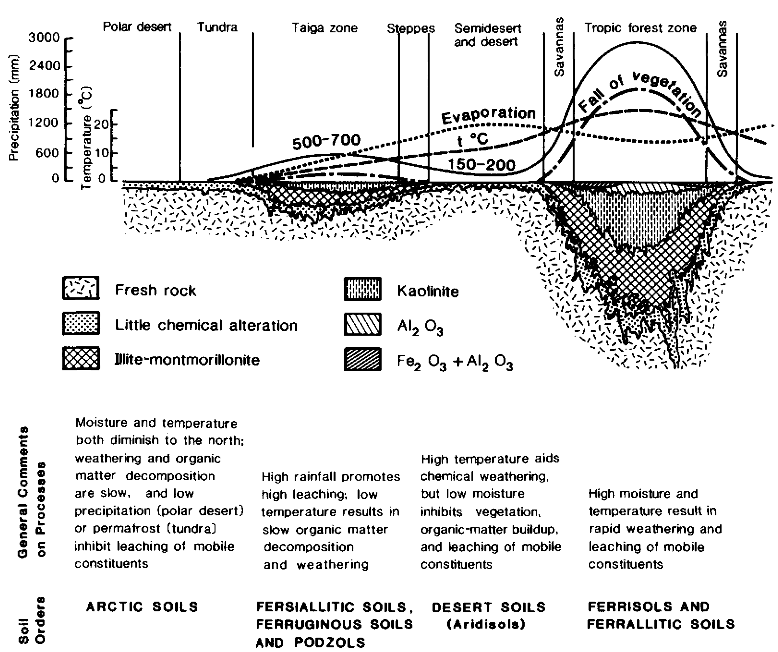

FIG. 2.2. Diagram of relative depth of weathering and weathering products as they relate to some environmental factors in a transect from the Equator to the north polar regions (after Strakhov 1967).

movement, as in the Cretaceous sandstones of southern Nigeria.

In tectonically active areas, rapid rates of uplift and consequent stream dissection can lead to long, steep (greater than 30°) slopes, on which saprolite development is arrested by high rates of erosion, including landsliding. In Papua New Guinea where there is greater than 2000 mm precipitation, between 3 and 10 m of saprolite is common. Here however it may be described as 'immature' (Haantjens & Bleeker 1970) as it contains broken rock as well as some kaolinite.

2.4.3. Geomorphological setting of the site

This affects the depth of weathering because the immediate slope and surrounding relief influence drainage and therefore rate of leaching. Furthermore, weathering is often less intense at very elevated sites because of lower temperatures. Geomorphological history helps date the age of the land surface, which indicates the earliest possible date for the start of profile development. In the humid tropics, interfluves and upper slopes of valleys experience enhanced subsurface drainage which allows deeper penetration of weathering. Permanent or seasonal surface streams usually excavate weathered residues and expose the bedrock. In the semi-arid tropics and savannas, interfluves and upper slopes experience strong sheet wash which may expose bedrock or ancient duricrusts; the eroded material often accumulates on footslopes to form thick accretionary soils. Ephemeral streams, usually not confined to channels, encourage weathering to penetrate deeply beneath valley floors.

In the wetter sub-humid and seasonal monsoon climates, deep weathering occurs below low-order stream valleys (locally known as bolis, dambos, vleis or biaxas). Higher-order seasonal or perennial rivers usually maintain rock channels (Thomas 1974), but deep weathering may occur where valleys follow lines of rock fracturing or where streams have shifted over broad floodplains for 10^4 to 10^5 years. Seepage zones around large hills (inselbergs) or in scarpfoot locations are often associated with deep weathering, even adjacent to fresh rock outcrops.

Deep weathered mantles in semi-arid tropical areas generally survive from former humid periods, often considered to be late Mesozoic or early Cenozoic in

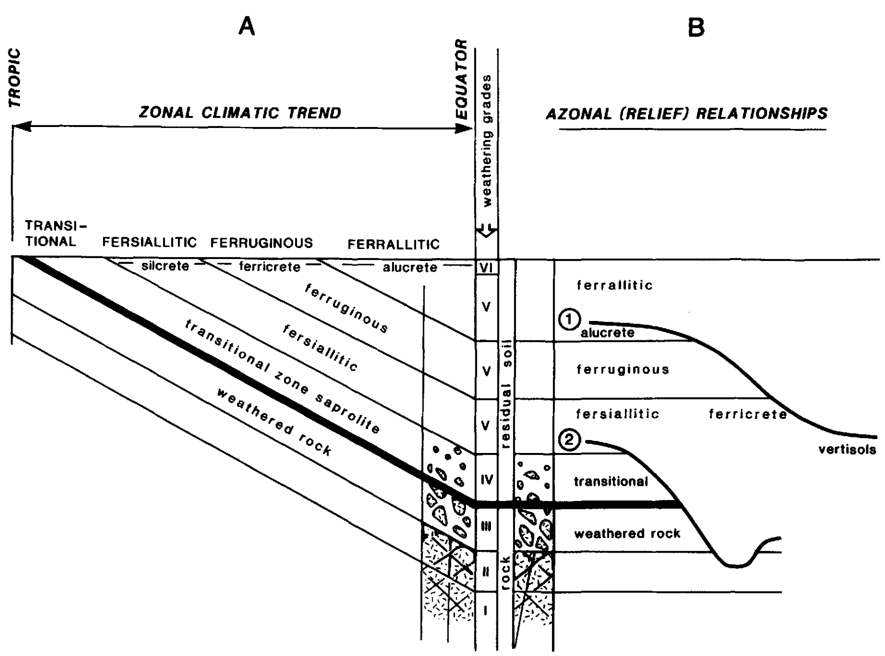

FIG. 2.3. Schematic diagram to relate weathering depth and grade with adopted residual soil classification in zonal and azonal contexts using the Strakhov model (Fig. 2.2). In (A), the intention is to demonstrate the general correspondences between residual soil class and weathering type as indicated by Strakhov and between weathering grade and residual soil type in a vertical profile. Such correspondences may be conceptually helpful but must be used with caution. In some tropical profiles, for example, there is a complete transition from fresh rock to ferrallitic soil materials over a distance of <1 m around residual corestones. In (B), 1 and 2 are examples of catenary sequences across hypothetical slopes developed in pre-weathered rocks, showing how different horizons of the weathering profile (residual soil and rock) may outcrop, and where other residual soil and duricrust types may develop.

age (Partridge & Maud 1987), and today are protected by laterites or silcretes. Deep mantles are also preserved beneath the forest cover in the humid tropics, even on slopes up to 20°. Such mantles become unstable after clearance and may even suffer slope failure under forest following prolonged periods of heavy rain.

2.4.4. History of weathering and erosion at the site

The depth of weathering is partly a function of the time available for the processes of rock decay to operate, but it also reflects the balance between weathering and removal by erosion. Terrain types such as plateaux, ridges and valleys, and lowland plains all differ in their histories of weathering penetration, and each may include contrasting terrain subtypes (Thomas 1974).

Ancient weathered landsurfaces in the interiors of Gondwana continents often display great albeit uneven depths of weathering, commonly exceeding 30 m and locally reaching some 100 m. Frequently, such landsurfaces are extensive plateaux of low relief capped by summit laterites, which are geologically old and may date from the early Cenozoic or Mesozoic in Africa and Australia (Mabbutt 1965, Butt 1981, Partridge & Maud 1987) (Fig. 2.3). The induration resulted from water table lowering and exposure following late Cenozoic dissection of the old planated landscapes. Such duricrusts also protect the lower profile (e.g. soft kaolinitic saprolite), which has often been deepened as dissection proceeded.

Derived from these landsurfaces are etchsurfaces (Thomas 1974, 1986; Adams 1975) or terrains partially or wholly stripped of their weathered mantles. In humid tropical regions, however, renewed weathering in valleys and on selected facets of the landscape has resulted in new profiles of variable depth and character; rocky inselbergs commonly break the mantled surface to give a relative relief of tens or hundreds of metres.

Where arid or semi-arid conditions were imposed on formerly humid regions, the dissected weathered land surface is often rocky with shallow soil profiles on most slopes and hills. Remnant deep profiles may be found beneath fossil duricrusts or within surviving basins of deep rock decay. Such landscapes are common in Western Australia and parts of Sahelian Africa.

Deep weathering also occurs beneath strongly uplifted basement terrains in peninsular Malaysia, Kalimantan (Indonesian Borneo) and Hong Kong. Mesozoic to late Cenozoic tectonic activity produced faulted ridge and valley landscapes, which are deeply weathered in response to the heavy annual rainfall of 2500 to 5000 mm and the dense rainforest cover.

2.4.5. Summary

Optimal conditions for deep weathered mantle formation include:

(a) wet equatorial or monsoon climate with rainfall from 2000 to 5000 mm/yr and past histories of moderate seasonality during the Quaternary and tropical latitudes throughout the Mesozoic and Cenozoic;
(b) passive plate margin cratonic surfaces underlain by mafic (dark) or intermediate crystalline rocks or arkosic sediments, and influenced by domal uplifts, faulting and fissuring, by intrusive and extrusive igneous activity and possibly by hydrothermal activity;
(c) watershed and plateau sites with moderate slopes of less than 15° which lacked incision or saprolite stripping during the Quaternary.

Adverse conditions for deep mantle formation are:

(1) long history of arid or semi-arid climate;
(2) mobile zones and abruptly folded, faulted and uplifted terrains underlain by felsic crystalline or quartzose sedimentary rocks;
(3) steep valleyside or sharp-crested sites with sharp relief;
(4) interfluve sites with little vegetation cover.

2.5. Profile features of engineering significance

2.5.1. Hard duricrust cappings

These features mainly include ferricrete, silcrete, possibly the softer alucrete or 'bauxite', and also calcrete or 'caliche'. Ferricrete duricrusts are widespread but have complex formative histories. Summit duricrusts, often 2 to 10 m thick, may have resulted from long histories of landscape development (Gaskin 1975; Butt 1981) involving sequences of humid tropical weathering, progressive desiccation due to climatic shifts, and a fall in the watertable due to incision of drainage. Lower slope laterites and ferricretes forming pediments and benches are generally younger and more detrital and often conglomeratic in origin. Groundwater laterite beneath lower valley slopes and valley floors is related to present and recent past groundwater regimes, and is generally thinner and less continuous. Calcrete forms at depths between 0.5 and 2.0 m in semi-arid fersiallitic soils; discontinuous and weakly indurated crusts often occur beneath calcareous surface horizons; massive indurated layers occur beneath non-calcareous horizons (Duchaufour 1982). Flaggy, lamellar calcretes form by recrystallization (Netterberg 1971) and possibly by replacement of silcretes. Thick calcretes often form in dry piedmont regions

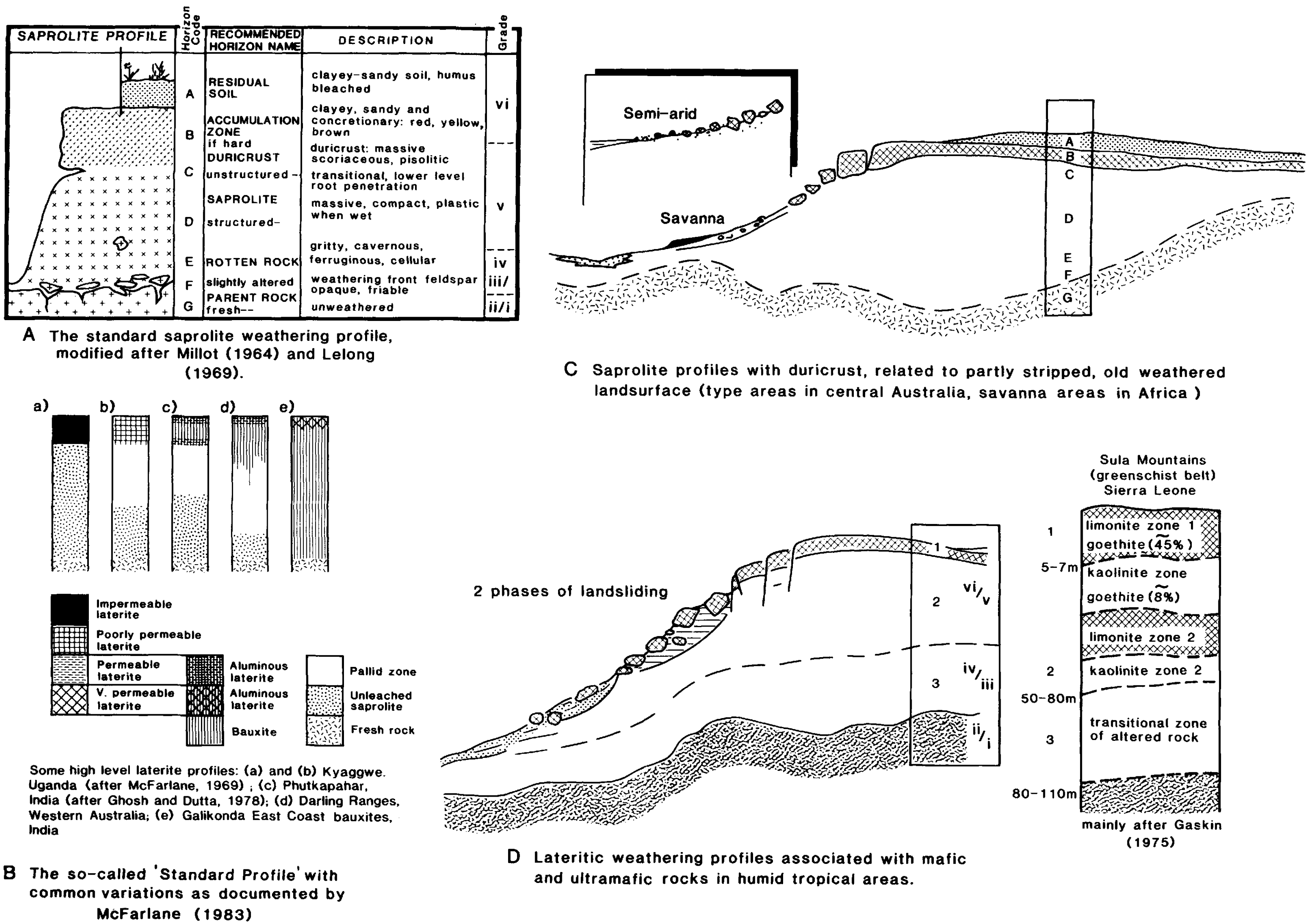

FIG. 2.4. Examples of duricrusted profiles, illustrating the 'standard' profile (A) and common variations (B), together with landscape associations in semi-arid (C) and in humid tropical (D) environments.

from bicarbonate moved laterally from adjacent limestone hills with a more humid climate.

2.5.2. Residual clay horizons within saprolites

Residual clay horizons within saprolites vary in clay content, clay type and horizon thickness according to climatic, geological and site factors. Soft plinthite usually from 1 to 3 m thick may be the precursor of some ferricretes and contains varying amounts of kaolinitic clay, Fe and Al sesquioxides.This classical 'laterite' described first from India may be soft in situ but hardens on exposure as along valley edges. Kaolinitic clay horizons may be very thick but often decrease in clay content with depth (Lumb 1962, 1965; Ruddock 1967).

2.5.3. Transition to fresh rock from saprolite

This may be sudden or occur gradually over many metres (Figs 2.4, 2.5, 2.6 and 2.7). Over crystalline rocks a fairly sharp transition to rock requiring diamond drilling can occur over a depth of less than two metres. This basal weathering front or basal surface of weathering (Berry & Ruxton 1959; Mabbutt 1961) is often well developed over massive granites, granodiorites, migmatitic gneisses and some metavolcanic rocks. Over more fissile rocks, such as mica

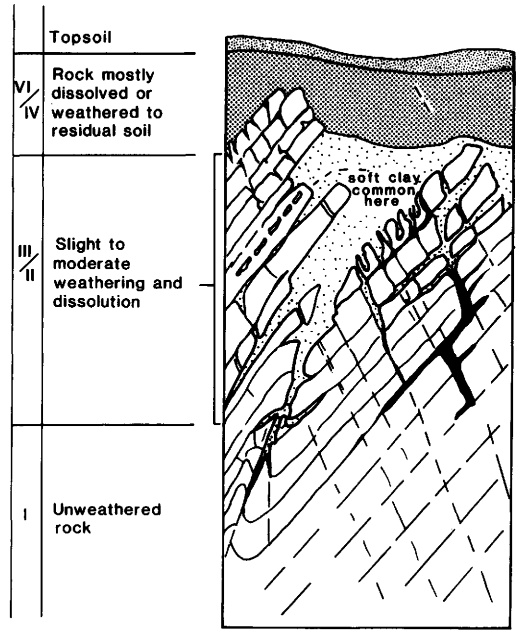

FIG. 2.6. Typical weathering profile for carbonate rocks. The occurrence of a saprolite Zone (V) is restricted to impure (silty/sandy) carbonates, while Zone IV characteristics occur mainly in chalky limestones. Soft clays often occur as cavity fillings and are not strictly in situ (adapted from Deere & Patton 1971).

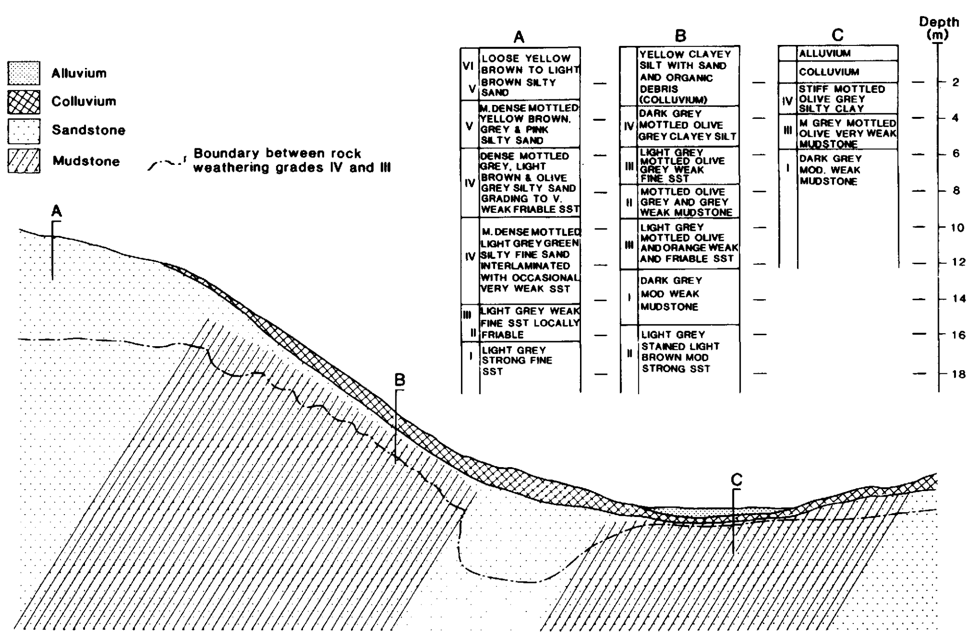

FIG. 2.5. Transect of weathering depths and profile characteristics in mixed sedimentary rocks, illustrated from Sarawak, East Malaysia (after Cook & Younger 1986).

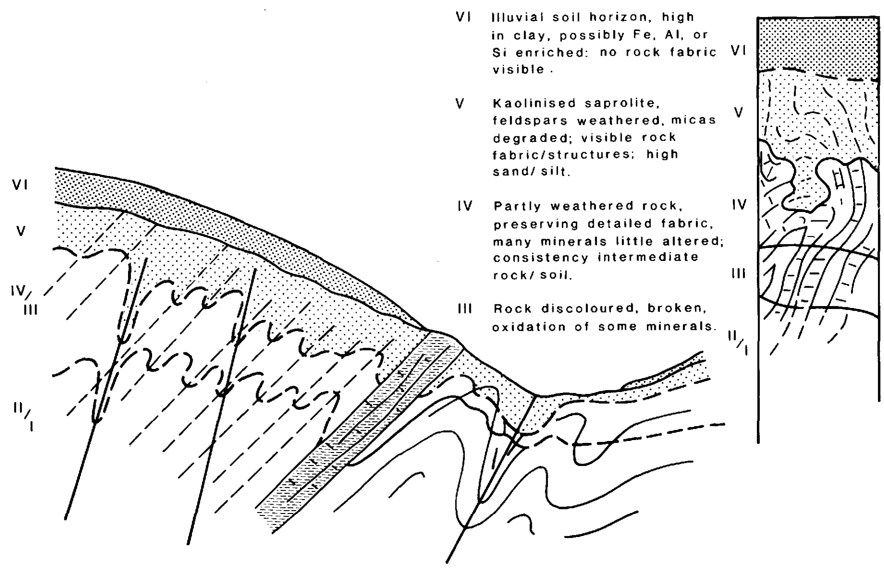

FIG. 2.7. Transect of weathering depths and profile characteristics over banded metamorphic rocks (adapted from Deere & Patton 1971).

schists and phyllites, the weathering front is usually less distinct and the transition to fresh rock may occur over tens of metres. Well jointed igneous rocks often form corestones, which become more abundant with depth but may be exposed on the sides of valleys cut into the weathered mantle. Most corestones are less than 2 m across although some are between 5 and 10 m in diameter. The base of weathering Grade IV is taken as the depth at which corestones exceed 50% by volume of the regolith. Conventional subdivision of such profiles is based on conditions in Hong Kong (Ruxton & Berry 1957) (Fig. 2.8), but it should be recognized that this sequence may be reversed locally as a result of variation in depositional history or fracture spacing. Prior erosion of saprolite may lead to surface accumulations of corestones, beneath which Grade IV or even Grade V materials may be encountered.

As pointed out in Chapter 1 tropical residual soil is defined as including all the material in weathering Grades IV, V and VI. An advantage of using the French system of classification is that it may be applied to materials down to and even beneath the base of Grade IV, whereas other systems are based on soil characteristics to a depth which may not even include the whole of weathering Grade VI. The French system could also be used by any subsequent Working Party considering weathering Grades I to III.

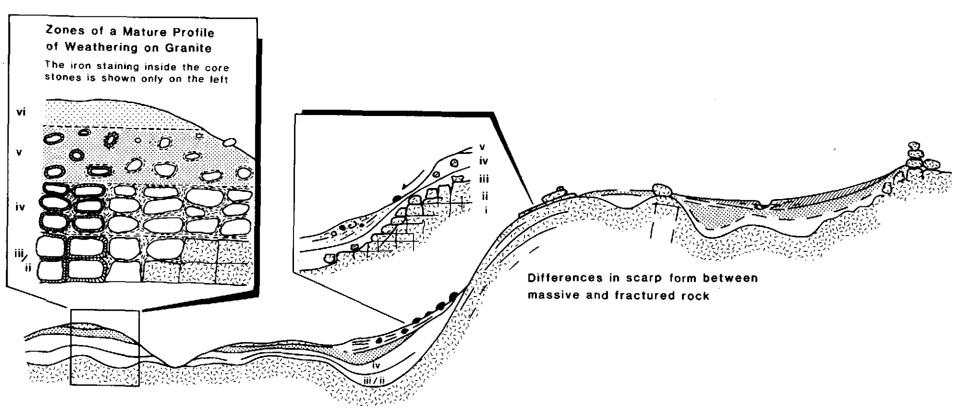

FIG. 2.8. Weathering zones in granitoid rocks across a complex 'two-storey' landscape (adapted from Ruxton & Berry 1957, 1961).

2.5.4. Total depth of weathering

In the absence of a sharp basal weathering front the total depth of weathering may be difficult to define. This is particularly true of many sedimentary and fissile metamorphic rocks. However, in fractured crystalline rocks weathering depth may often be determined quite accurately, although the mantle thickness may vary abruptly across some terrains. Fresh outcrops often give way to troughs of weathering 15 to 20 m deep over horizontal distances of 100 to 200 m; and quite sudden depth increases from 30 to 50 m are known (Fig. 2.9).

2.5.5. Transported soils

Transported soils are not specifically dealt with in this Report, but as they are common in nature some comment is required. Soils derived from sediments which appear typically in higher latitudes (loess, glacial deposits, gelifluction deposits, etc.) are of course rare or unknown in the tropics. However the residual mantle of saprolite in the tropics is commonly overlain or replaced by various transported sediments brought in by slope movements such as free fall, landsliding, rain splash, sheet wash or mudflow, or by aeolian or fluvial activity.

Scree slopes are commonly underlain by weathered rocks, particularly where rapid infiltration is encouraged by coarse surface debris. Landslide debris may extend for 1 to 2 km across piedmont footslopes and accumulate over weathered bedrock to depths exceeding 10 m. More commonly residual soils are covered by between 1 and 5 m of faintly bedded sandy or loamy sediment often described as colluvium. At the base of this pedisediment there is often a stone-line or gravel up to 2 m thick, which is usually composed of resistant rock fragments (e.g. vein quartz). The processes resulting in stone lines are complex and include vertical sorting by termites and formation of lag gravel as finer components are carried downslope by strong surface wash. In semi-arid regions, lag gravels may appear at the surface. In humid regions burial of the lag gravel by finer colluvium may indicate a climatic change.

The diagnostic features of transported soil horizons include: absence of rock structure; selective sorting by particle size; weak stratification; fining downslope; absence or weak development of soil structure and presence of foreign rock material derived from upslope sites. The junction with an underlying residual soil is commonly marked by changes in particle size distribution, colour and chemical composition in addition to the stone-line or gravel layer. Buried soils within the colluvium often indicate two or more episodes of deposition with intervening periods of stability, possibly resulting from Quaternary climatic changes. Many duricrusts, particularly lower slope laterites (see Section 2.5.1), have formed at or near the base of the transported layer, the cementing iron oxides having been precipitated from groundwater moving laterally over the underlying saprolite or bedrock.

Colluvial processes are very active in savanna environments (Thomas 1986), even under forest. The drape of transported soil across most intermediate and lower slopes is a widespread feature in the tropics. As such materials have different geotechnical properties from underlying saprolite, they are of considerable engineering significance.

2.6. Lateral variability of tropical residual soils

2.6.1. Regional patterns of weathering

Cratonic surfaces draining into the Atlantic and Indian Oceans (including much of tropical Africa, America, Australia and India) experienced an increasing continental 'freeboard' and strong dissection during at least the last 100 Ma. Fragments of old weathered landsurfaces, which have survived in interior locations protected by thick duricrusts, are correlated by some with continent-wide erosion surfaces (peneplains or pediplains) (Fig. 2.4). Uplifted plateaux of granitoid rocks are often bounded by a marked escarpment separating upper and lower landsurfaces. Such 'two-storey landscapes' (Ruxton & Berry 1961) display complex patterns of weathering zones and rock outcrops (Fig. 2.8). Elsewhere, denudation has differentiated landscapes according to rock susceptibility to weathering: mafic rocks emerge as plateaux protected by duricrusts, more felsic terrains form granite or gneiss inselbergs, core strewn slopes and rock-floored valleys, and quartzose rocks form bare ridges. Examples of these terrains are found in the faulted, domal uplifted areas of West Africa and Guyanas. The steep foliation common in these metamorphic terrains may lead to rapid changes in depth of weathered mantle. For example, the deep decay of mica schist adjacent to a rock-cored quartzite ridge could promote instability of the steep flanking slopes and catastrophic mass movements under extreme meteorological conditions. This occurs under savanna woodland in areas of modest rainfall (between 700 and 1000 mm/yr) in eastern Zambia as well as in wetter areas such as the Owen Stanley Mountains in Niuguini.

Extensive planated landscapes, developed on crystalline rocks, commonly exhibit repeated basins or troughs of weathering with intervening domal or linear rock highs which may break the surface as outcrops. More continuous deep weathering is found in connection with fissile metasedimentary and

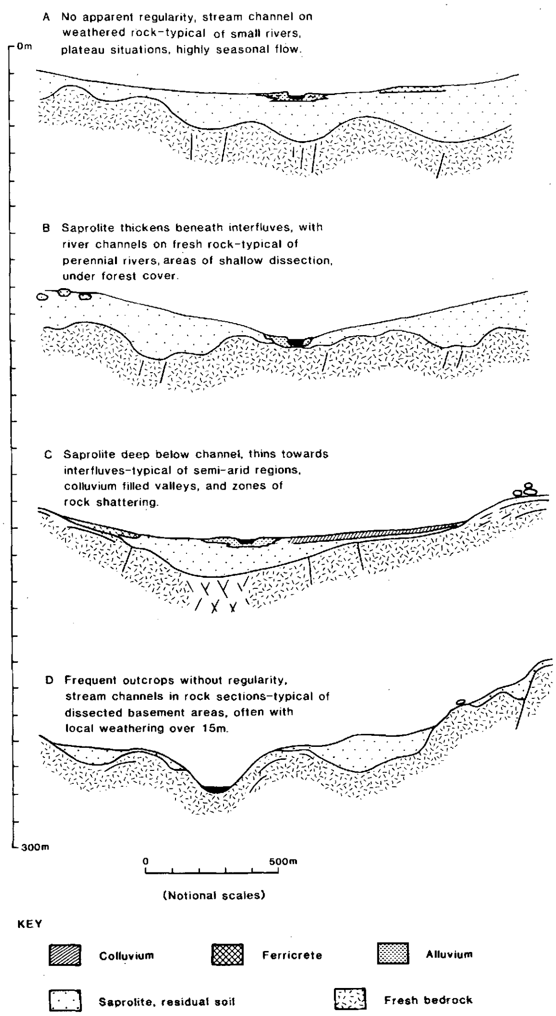

FIG. 2.9. Examples of transverse valley profiles illustrating common patterns of variation in weathering depths.

metavolcanic formations which often carry thick lateritic profiles.

In the absence of extensive duricrusts, dissection of deeply weathered terrain in the humid (forested) tropics produces a characteristic multiconvex relief within which rock outcrops and corestones appear almost randomly (Fig. 2.10B), although the terrain is compartmented according to regional structures. Uplifted Mesozoic 'basement' rocks in Kalimantan, Indonesia, produced this type of relief; the amplitude of the domal convexities increases inland from the coast. Where more resistant rock types occur however steep spines of rock with shallow weathering profiles may be surrounded by a piedmont or 'lower storey' landsurface of low relief with deep weathering.

2.6.2. Local patterns of weathering

Local weathering patterns are seen between interfluve and valley floor, between hilltop and hillfoot (Figs 2.9 and 2.10) and within essentially flat areas on divides and in valleys. Many patterns reflect moisture movement and retention in the regolith and rock voids as well as rate of surface erosion (truncation of profiles). Thus water movement, leaching and weathering rates are accelerated beneath crests and upper hillslopes by renewal of groundwater, provided input from rainfall is frequent. In seasonally arid climates preferential weathering may occur in hillfoot locations where renewal of groundwater is most frequent and soil moisture is maintained during the dry season. However, in humid forested areas with minimum seasonality, deep profiles are found in many parts of the landscape including upper slopes and steep (*c.* 20°) valley sides (Figs 2.8 and 2.10C).

Most rivers in tropical regions flow in rock channels, often over channel-fill sediments. However deep weathering may occur beneath streams that follow shatter zones, beneath indistinct channels formed by small ephemeral streams and beneath older floodplain deposits (Fig. 2.9). Saprolite mantles are widely stripped from hillslopes and steep interfluves and deposited within river valleys or on piedmont slopes during the drier climatic phases of the Quaternary. This has commonly resulted in hillslopes with shallow regoliths and corestones, especially over granites in areas such as the Jos Plateau, Nigeria, where the annual precipitation is 1200 to 1400 mm and interior Sierra Leone with an annual precipitation of 2000 to 2500 mm (Fig. 2.4).

2.6.3. Profile variations

Topographic control over soil properties is particularly strong in tropical environments (Young 1976), reflecting the importance of lateral movement of water and soil material down-slope as well as down-profile. Successions of soils down a slope which are repeated in a pattern across the landscape or 'land system' (Christian & Stewart 1968; Thomas 1969), are referred to as catenas (Milne 1935). Simple catenas (toposequences) are formed on one parent material, whilst compound catenas have a more complex origin. They may be lithosequences where the variation derives principally from differences in substrate lithology and mineralogy, but most also show profile differences attributable either to downslope movement of fine soil particles and material in solution or to site differences related to slope angle and depth of the watertable.

Some of the more common sequences of soil properties and profiles, especially between interfluve and valley floor, are shown in Figs 2.11 and 2.12, but many local variations exist (Ollier 1976; Moormann

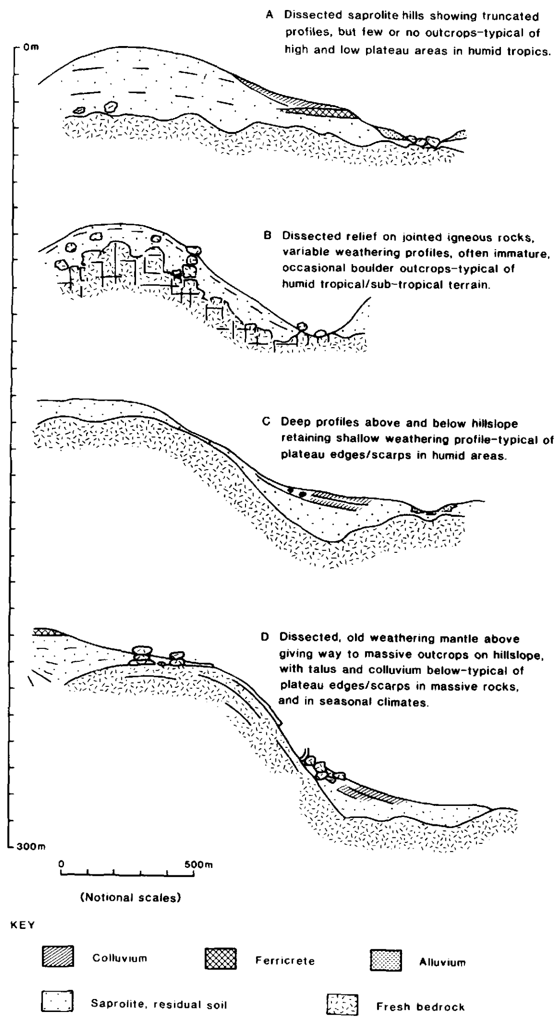

FIG. 2.10. Examples of hillslope profiles illustrating common sequences of weathering and landforms.

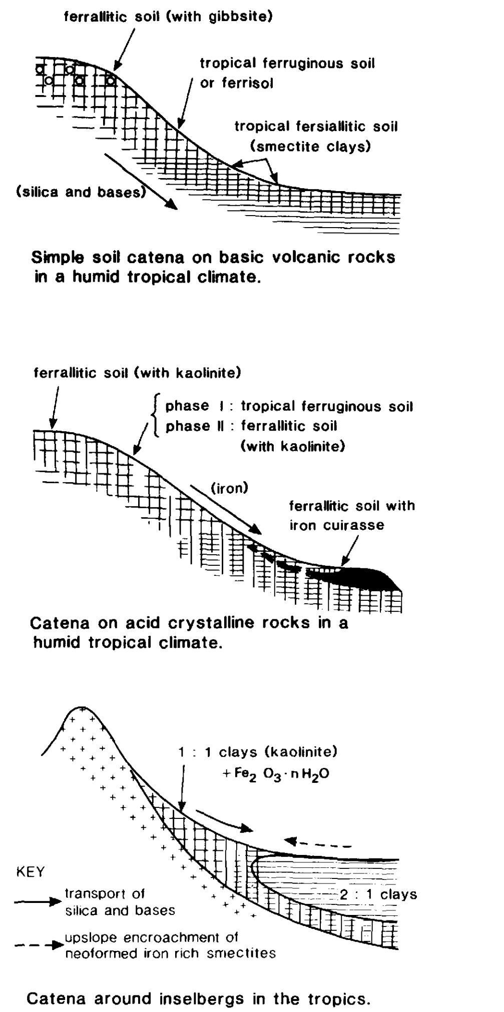

FIG. 2.11. Characteristic soil catenas found on igneous rocks in the tropics (adapted from Duchaufour 1982).

1981; Young 1976). Strongest leaching is likely to occur beneath upper slopes and mobile ions including silica, iron and bases progressively accumulate, often recombining to form new clay minerals towards footslope locations where drainage is impeded. This may lead to the formation of a lateritic horizon towards the base of the slope. On a single parent material, such as basic volcanic rock, ferrallitic soils on upper slopes often give way to ferrisols and fersiallitic soils in sequence downslope (Fig. 2.11). Similar simple catenas may develop on plateau surfaces with low relief (5 to 20 m). Compound catenas produce various patterns depending on parent material and climate (Figs 2.3 and 2.8). Lateral or vertical variations in substrate may influence clay content, iron segregation and a wide range of other properties. Many tropical catenas result from dissection into a deeply weathered landsurface, the members of the catena occurring on different zones of the weathered rock (Figs 2.3 and 2.13).

As most duricrusts involve the accumulation and immobilization of metal cations, they tend to form at sensitive levels within profiles, for example where there is a narrow range of watertable fluctuation, and in lower slope positions within catenas. The iron accumulations forming beneath lower valley side slopes, piedmont footslopes, shallow valley floors (e.g. dambos) and other zones of convergent

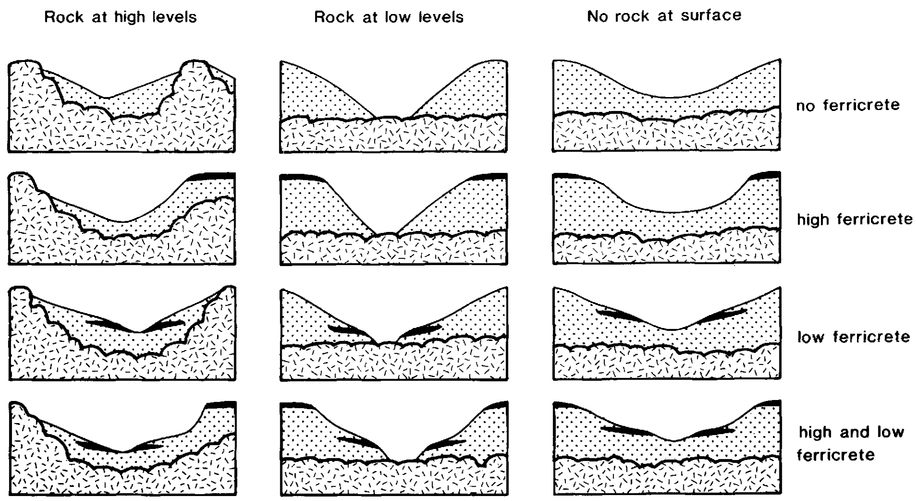

FIG. 2.12. Catena types formed by dissection into a deeply pre-weathered landscape, illustrating the possible occurrences of ferricrete in the landscape (after Ollier 1976).

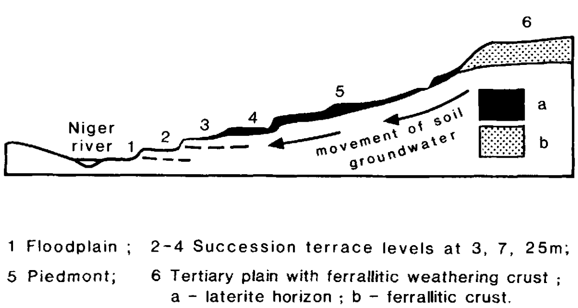

FIG. 2.13. Multiple laterite crusts formed as benches on River Niger terraces in the Kankan region (after Pelisier & Rujeri 1981).

groundwater flow are termed groundwater laterites (Thomas 1986) (Fig. 2.11). Where such features are dissected the laterites form duricrusted benches marking successive erosional levels (Figs 2.12 & 2.13).

2.6.4. Summary

Lateral variations in tropical residual soils result from two main factors:

(a) a spatial pattern of variable depth of weathering, sometimes to many tens of metres;

(b) catenary patterns of soils superimposed on this irregular weathered mantle.

Both demonstrate the importance of inherited materials within the contemporary landscape. Particularly on tropical cratons, the profile and catenary variations in the properties of residual soils commonly reflect the degree of preservation or truncation (Butt 1981) of deep weathering profiles. These have developed over long time periods, perhaps from 10^6 to 10^7 yr, during which fluctuations of climatic and other soil forming conditions may have been profound. More recent environmental changes associated with the later Quaternary mainly influenced the near-surface soil horizons, many of which provide evidence for lateral transfer of sediment in the landscape.

Appendix specific to Chapter 2

Approximate equivalents of soil map units in the French, FAO-UNESCO and American systems. The purpose of this table is to assist the engineering interpretation of various types shown on soil maps published for tropical regions.

French classification (Duchaufour)	F.A.O. classification	American classification
Fersiallitic soils: CEC > 25 mEq, free iron is usually >60% of the total content, 2:1 clays dominant.		
tropical brown eutrophic soils	chromic cambisols	perudic and udic tropepts
subtropical brown soils	chromic cambisols, chromic and haplic luvisols	xeric and ustic ochrepts, rhodic xeralfs and haplic udalfs

French classification (Duchaufour)	F.A.O. classification	American classification
subtropical brown soils with calcic crust	calcisols	xeric and ustic ochrepts
tropical red soils	chromic luvisols	pale and rhodic ustalfs, xeralfs and udalfs
subtropical brunified red soils	chromic luvisols	pale and rhodic ustalfs, xeralfs and udalfs
subtropical truncated red soils	chromic luvisols	pale and rhodic ustalfs, xeralfs and udalfs
subtropical red soils with calcic horizon	calcic luvisols	pale and rhodic ustalfs, xeralfs and udalfs
modal acid fersiallitic soils	haplic alisols	pale and rhodic ustalfs, xeralfs and udalfs
hydromorphic acid fersiallitic soils	gleyic and ferric alisols	ochric and albic tropaqualfs
Ferruginous soils: CEC 16–25 mEq throughout, Bt horizon always present, kaolinite dominant clay, but 2:1 minerals also present.		
eutrophic	chromic luvisols	pale and rhodic tropudalfs, tropustalfs and xeralfs
oligotrophic	umbric and haplic alisols	pale & rhodic tropudults, tropustults and palexerults
hydromorphic plinthic	plinthic alisols, plinthosols	plinthic ustalfs, udalfs, xeralfs, udults, ustults and aquults
hydromorphic pseudogleyic	gleyic and ferric alisols, gleyic luvisols	paleaquults and tropaquults
hydromorphic indurated	—	—
Ferrisols: CEC < 16 mEq in upper B horizon, 16–25 in lower B, kaolinite dominant, but 2:1 minerals also present.		
with Bt horizon	rhodic and haplic nitosols, ferric and haplic acrisols, chromic luvisols	pale and rhodic udults, ustults and tropudults
with Bw horizon	ferrallic cambisols	eutric and haplic ustox and orthox
hydromorphic plinthic	plinthic acrisols and alisols, plinthosols	plinthic udults, ustults, aquults,humults and aquox
hydromorphic pseudogleyic	gleyic and ferric acrisols and lixisols	ochric and umbric aquox
hydromorphic indurated	—	—
humic	mollic and umbric nitosols, umbric acrisols and albic lixisols	sombric, pale, trop and haplic humults, humox, sombric ustox and orthox
Ferrallitic soils: CEC < 16 mEq throughout, little or no 2:1 clays present.		
ferrallitic soils with kaolinite	ferralsols	orthox
ferrallitic soils with gibbsite	ferralsols	gibbsiaquox, gibbsihumox, gibbsiorthox
ferrites	ferralsols	acrorthox, eutrorthox
ferrallites	—	—
allites	ferralsols	gibbsiorthox
hydromorphic ferrallitic soils	ferralsols	ochraquox, umbraquox
ferrallitic soils with plinthite	plinthosols, plinthic ferralsols, acrisols and lixisols	plinthaquox, plinthic acrorthox and haplorthox
indurated ferrallitic soils	—	petroferric acrohumox

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Corestone profiles developed in granodioritic rocks, NSW, Australia. Sub-tropical weathering has led to fersiallitic phase of weathering. Plate 1, Zone V; Plate 2, Zone IV; Plate 3, Zone III; Plate 4, Zones III/II (see Fig. 1.1).

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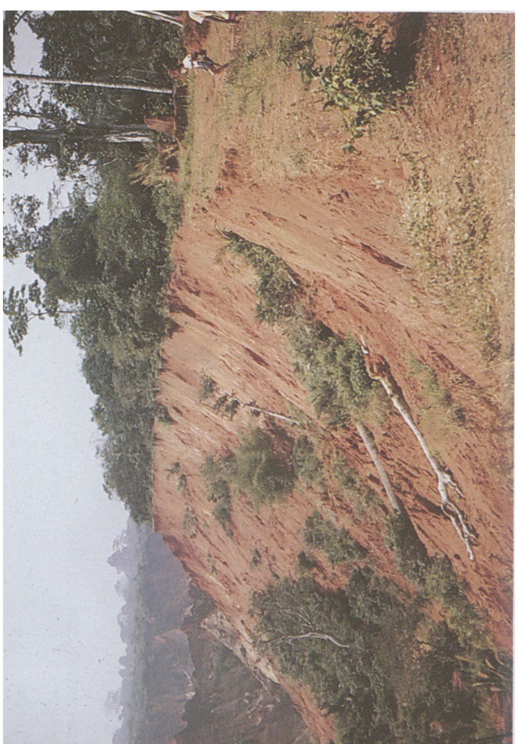
Aspects of weathering profiles in granitoid rocks. PLATE 5. Ferruginous phase of weathering in granite on the W. Australian plateau. Note sharp interface (basal weathering surface) between fresh rock and saprolite, and concentration of iron oxides in upper profile. PLATE 6. Ferrallitic phase of weathering in granodiorite under equatorial conditions, Singapore. PLATE 7. Granite weathering profile in steep terrain under tropical forest, W. Malaysia. On the steep slopes (>20°), the residual soil remains in equilibrium at a fersiallitic phase of weathering despite humid tropical climates. PLATE 8. Deep kaolinisation (ferrallitic) beneath thick ferricrete crust, Kano, Nigeria associated with ancient (possibly late Mesozoic) land surfaces.



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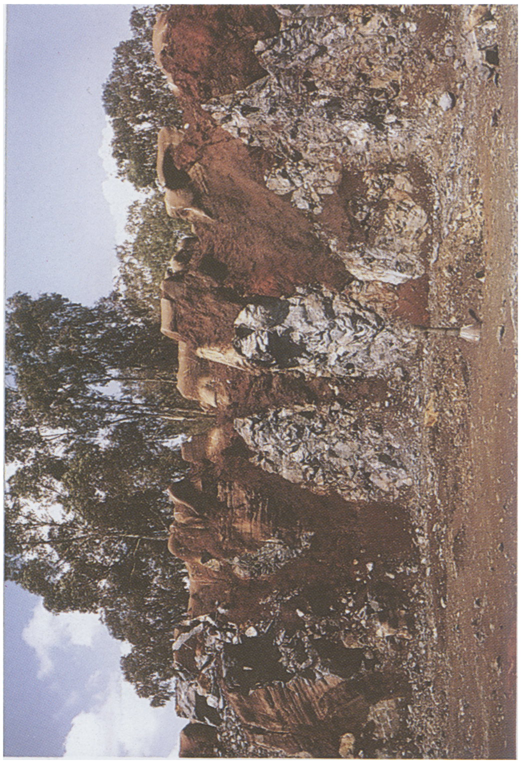

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PLATE 9. Ferrallitic weathering in Cretaceous sandstones, southeastern Nigeria, exposed in spectacular gully systems near Nanka; the base of the weathered zone is indeterminate. PLATE 10. Weathering of dolomite under sub-tropical conditions in South Africa. Residual soil (2:1 clays high in Mg) accumulates between pinnacles. PLATE 11. Polygonal soil structure in sodic (Vertisol) soil, eastern Zambia. Mobile ions (Na, K) accumulate in poorly drained depressions such as the 'dambos' of central Africa, under seasonal rainfall conditions. PLATE 12. Silcrete fragments derived from ancient weathering profile in Australian arid zone, western NSW.


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PLATE 13. Residual 'laterite' (ferricrete) forming in basic igneous complex (gabbro), Freetown Peninsula, Sierra Leone. The rock fabric is preserved as the iron-rich rock (10–20% Fe total) is weathered beneath a well drained site. PLATE 14. Residual 'bauxite' (alucrete) formed in feldspathic gneiss, Mokanje, Sierra Leone. Formed on typical hilltop site in forest zone (>2500 mm/yr rainfall). PLATE 15. Groundwater laterite developing in sandy-clay sediments over basalt lavas, NE. Queensland, savanna woodland zone. PLATE 16. Calcrete formed in alluvium over dolerite and associated with fersiallitic phase of weathering, South Africa.

3. Soil classification

3.1. Objective

The purpose of this chapter is to define the terms and provide an explanation of the formal classification of residual soils adopted in this Report. The classification is genetic in character (based on the work of Duchaufour 1982) and arises naturally from the processes described in Chapter 2. In the tropics the dominant processes yield characteristic mineral assemblages that not only form the basis for formal pedogenetic studies but also govern engineering behaviour. Thus a central theme in this chapter is to emphasise the scientific basis for the classification adopted. A comparison with commonly used geotechnical terms is also presented.

3.2. Background

Traditionally, the classification of residual soils has been on the basis of pedogenetic criteria, which is the logical basis for a scientific classification. Unfortunately at least three major pedological classification systems exist for tropical soils. Each system is complex in terminology and relies on subtle changes in the soil profile; moreover, pedological classifications relate to profiles, any one of which may contain several material types. Thus this basis of classification is less helpful to the engineering geologist or geotechnical engineer attempting to classify such soils in terms of their geotechnical characteristics and hence engineering behaviour (Netterberg 1975; Nogami & Villibor 1981; Queiroz de Carvalho 1981; Netterberg & Weinert 1983). It is for this reason that many other attempts at classification have also been published, each having a particular end use in mind (Table 3.1).

The majority of current classifications of tropical residual soils can be divided into four types.

(1) Those that depend on environmental criteria and are therefore useful in a geographical distributive sense, especially for land systems mapping.

(2) Those that employ strict pedological criteria, such as the silica–sesquioxide ratio.

(3) Those that merely extend the standard geotechnical soil classifications, such as the USCS or HRB classifications, therefore not fully admitting tropical soils as a special category.

(4) Those that develop a special parameter of particular relevance to a specific end use of tropical soil as an engineering material.

None of the methods gives a satisfactory coverage of the variety of soils that may exist however.

3.3. Genetic classification

The basis of the genetic classification proposed by the Working Party is purely pedogenetic, in which the breakdown of parent materials, both primary and sedimentary, takes place within a complex tropical environment. For classification purposes, however, it is only necessary to recognize broad climatic groupings of wet tropical, seasonal (dry) tropical and cooler climates modified by altitude. Another important element is the drainage status, impeded or free. These processes yield certain associations of secondary duricrusts. They can be described in terms of five main soil profile types and their associated 'cretes'.

Each soil group may be further subdivided into very small units (Table 3.2). An indication of the many divisions which might be adopted is given in the classification based on the formal tables of Summerfield (1978, 1987), Goudie (1973), Goudie & Pye (1983), Valeton (1983) and Duchaufour (1982). These divisions have been modified by the Working Party in order to attain some consistency in appraisal. It should not be expected that all workers will accept the fine detail provided as being the definitive classification. It is considered, however, that possible disagreement on these matters is relatively unimportant because, for engineering purposes, fine distinctions are often unnecessary and guidance on geotechnical behaviour may usually be obtained from definition of the broader categories only.

The philosophy behind the classification of the mature soils adopted is summarized by Duchaufour (1982) as follows.

> 'The three types of weathering: (i) fersiallitization (2:1 clays dominant); (ii) ferrugination (kaolinite and 2:1 clays); and (iii) ferrallitization (kaolinite and gibbsite), in fact do not belong to different cycles but to three phases of the same cycle, the end stage of which is ferrallitization. In subtropical climates with a marked dry season stage (i) is rarely exceeded; in a dry tropical climate development stops at stage (ii); it is only in humid equatorial climates that stage (iii) is reached. The increase in the speed of pedogenesis, owing to rise of temperature on the one hand and increase of precipitation on the other, is fundamental to the final equilibrium stage that is reached.'

The formal classification is therefore divided into two basic divisions: duricrusts and mature soils. The descriptions are provided on the assumption that the

TABLE 3.1. *Previous classifications and their defining properties*

Defining Property	Clare (1957)	Winterkorn & Chandrasenkharan (1951)	Novais Ferreira (1969)	Correia *et al.* (1969)	Ruddocks (1969)	Little (1967)	Little (1969)	Gidigasu (1971)	United States Geological Survey (1986)	Highway Research Board	Vallerga *et al.* (1969)	Lal & Bindra (1981)	Eklu-Natai & Muller (1981)	Medina & Preussler (1980)	Medina & Preussler (1982)	Vargas (1969)	De Graft-Johnson *et al.* (1969)	Arulanan dan (1969)	Queiroz de Carvalho (1981)	Lohnes & Demiral (1973)	Nogami & Villibor (1981)
Pedogenic	*																				
Geology						*	*	*													
Topography					*																
Water table					*																
Saprolite																					
Weathering						*	*														
Climate								*													
Silica/sesquioxide		*	*																		
Si, Al, Al content				*																	
Particle size								*	*	*	*	*	*	*	*						
Clay (%)								*													
Shrinkage								*													
Atterberg Limits									*	*	*	*	*	*	*						
Organic (%)													*								
Moisture equiv.												*									
Uniformity													*								
Durability											*										
Heap strength													*								
Cation exchange													*								
CBR														*	*						
Activity																*					
Modified AIV																	*				
Electrical response																		*			
Lime reactivity																			*		
S. gravity																				*	
Void ratio																				*	
Cohesion																				*	
MCV																					*
Immersion wt loss																					*

TABLE 3.2. *A formal classification of residual soils*

Subdivision	Classification Criteria Groups	General Characteristics
A: Duricrusts		
Silcrete	a. Grain supported fabric	Skeletal grains in a self-supporting matrix. Optically continuous overgrowths chalcedony, micro-quartz cryptocrystalline and opaline alternatives.
	b. Floating fabric	Skeletal grains floating in matrix, not self-supporting. Massive glaebules sometimes present.
	c. Matrix fabric	Skeletal grains, massive glaebules absent in some forms, common in others.
	d. Conglomeratic fabric	Detrital content.
Calcrete	a. Calcified soils	Usually loose or soft soil weakly cemented by $CaCO_3$.
	b. Powder calcrete	Fine, usually loose powder, $CaCO_3$ with few visible particles. Little nodular development.
	c. Nodular calcrete	Nodules or concentrations in a loose structureless matrix
	1. Nodular	
	2. Concretionary/concentric	
	d. Honeycombe	Stiff to very hard open textured calcrete with voids usually filled with soil.
	1. Coalesced nodules	Cemented pebbles and fragments coalesced by laminar rinds.
	2. Cemented	
	e. Hardpan calcrete	A firm to very hard sheet-like layer always underlain by softer or looser material and seldom less than 45 cm thick. May be pseudo-laminated.
	1. Cemented honeycombe	
	2. Cemented powder	
	3. Recemented	
	4. Coalesced horizontal nodules	
	5. Case hardened calcic	
	f. Laminar	Firm to hard finely laminated undulose sheet layers, frequently capped by hardpan.
	g. Boulder	Varies from discrete to coalesced hard to very hard boulders in a usually red sand matrix.
Gypcrete	a. Desert rose	Individual, twinned and ingrown crystal clusters in loose sand matrix at capillary level.
	b. Mesocrystalline	Subsurface crusts, euhedral or lenticular.
	c. Indurated	Surface crusts—microcrystalline.
	1. Powder	
	2. Indurated alabastine	
	3. Alabastine cobbles	
	d. Evaporitic	Horizontal laminae or occasionally layer bedding forms.
	1. Laminated	
	2. Bedded	
	e. Gypsum rich dune sand	Loose or lightly cemented, often in dune form.
Ferricrete	a. Water table cuirasses	Occur at breaks of slope and basin margins. Iron carried by lateral circulation.
	1. Local	Accumulates in topographic lows as goethite or haematite, Localized segregation.
	2. Plinthite	Red patches of haematite.
	3. Petroplinthite	Irreversibly indurated by water table fall.
	b. Plateau cuirasses	Very thick on erosion surfaces. Concentrated in climatic zones with marked seasonal contrasts. Thickens laterally. Goethite replaced by haematite until dominant.
	or	
	a. Pisolitic	Welded concretions, unbanded to pseudo-rounded.
	b. Scoraceous and vesicular	Accumulated in old network of fissures of a polyhedral or prismatic horizon.
	c. Petroplinthite	Induration of plinthites often vesicular.

TABLE 3.2. *Contd.*

Subdivision	Classification Criteria Groups	General Characteristics
Alcrete (Alucrete)	a. Pisolitic in plinthites b. Scoraceous and vesicular c. Petroplinthite	Varieties as for ferricretes.
B: Mature soils		
Vertisols	a. Vertisols (*sensu stricto*)	Swelling clays overwhelming.
	1. Developed (Inc. black cotton soils)	Ratio of ferric iron to total iron high. Clays of neoformation and aggradation dominant.
	2. Slightly developed	Parents often crystalline and volcanic. Deep cracking and compaction with dessication.
	integrade	
	b. Coloured vertic soils	Characteristic of humid tropical climates with short dry season. Often on crystalline basic or volcanic rocks. Poor drainage.
	1. Integrades and ferruginous	Differences occur with degree of maturity of organic and iron content.
	2. Vertic tropical entrophic brown soils	High structure, clay content.
Fersiallitic Andosols	a. Vitrisols	Young andosols rich in volcanic glass, <10% organo-mineral complexes.
	b. Andosols (*sensu stricto*)	
	1. Humic andosols	Little profile differentiation. Strongly developed with >10% organo-mineral complexes. Slight decrease of organic material with depth. All horizons grey-black. Allophanic.
	2. Differentiated andosols	Marked downward decrease in organic material. Brown B horizon. Little or no silicate clay. Occurs on massive indurated rocks.
	3. Hydromorphic	Constantly soaked. decomposition of organics slow. Peaty, porous, but a lot of water retained. Complete reduction of iron.
	intergrade	
	c. Andic soils	Rapid mineralization of organic material concentrated at surface. Kaolinization limited, silica poor. Hydroxide, gibbsite-goethite.
Fersiallitic (*sensu stricto*)	a. Fersiallitic Brown soils	Young, therefore different from eutrophic brown soils. Not as deep as many tropical soils. Organic. Not rubified. 2:1 clays plus montmorillonites.
	1. Tropical Brown Eutrophic	
	2. Subtropical and Meditteranean	(*not considered further*)
	b. Modal Fersiallitic Red Soils	Common on basic rocks. Older soils rubified. 2:1 clays degrading to kaolinite. Loss of silica. Kaolinite not dominant. May have a calcic horizon.
	1. Tropical Fersiallitic Red Soil	
	2. Subtropical and Mediterranean	(*not considered further*)
Ferruginous (*sensu stricto*)	a. Argillic (Bt horizon present)	Kaolinite dominant. 2:1 clays subordinate. Gibbsite absent. Lower horizons kaolinitic saprolite. Most clays by neoformation. Development strongly influenced by age. Kaolinization by gradual degradation of montmorillonite, illite, interstratified clays and by kaolinization of feldspar.
	1. Eutrophic Ferruginous	Base saturation >50%.
	2. Oligotrophic Ferruginous	Base saturation <50%.
	3. Hydromorphic Ferruginous	

TABLE 3.2. *Contd.*

Subdivision	Classification Criteria Groups	General Characteristics
	b. Ferrisols (Bt horizon not essential)	
	1. Ferrisol, weak Bt	Diffuse accumulation of clay.
	2. Ferrisol, weathered Bt	Without diffuse accumulation of clay.
	3. Hydromorphic	With segregation of iron.
	4. Humic	At high altitudes may have gibbsite.
Ferrallitic (*sensu stricto*)	a. Ferrallitic	Profiles retain most of iron and aluminium. Some silica and all bases removed. Profile acidifies rapidly. Neoformal clays are kaolinites. Some free aluminium as gibbsite. Usually reduced to quartz, kaolinite, gibbsite and ferric oxides.
	1. Ferrallitic (Kaolinitic)	Gibbsite absent.
	2. Ferrallitic (Gibbsitic)	Gibbsite dominant.
	b. Ferrallites	
	1. Ferrites	On ultrabasic rocks. Poor in aluminium. Silica and magnesium removed. Iron left as goethite.
	2. Allites	Hydromorphic ferrallites, well drained, permeable, but humid. Iron mobilized by reduction and removed. All that remains is gibbsite—uniformly white.
	c. Ferrallitic (with hydromorphic segregation of iron)	Zones of plastic regolith, mottled zone is waterlogged. Iron poorly mobilized.
	1. Hydromorphic	Very humid but well drained.
	2. Plinthitic	Downslope forms on badly drained areas.
	3. Indurated	Iron transported over great distances. Acid water tables. At springs.

This classification is based on Summerfield (1978, 1983), Goudie (1973, 1983), Valeton (1983) and Duchaufour (1982).

soils are well developed and in a stage of biostasis; that is, they are broadly in balance with their conditions of formation and may be regarded as stable in terms of their major diagnostic characteristics (see Chapter 2). Of course, clearly there will be many variations depending on age, topographic position and other factors, and in the field the soils may be less or more mature, less or more complete, eroded, truncated or redeposited. They may have been subjected to environmental change and be in the course of appropriate modification. They may even be entirely relict. Nevertheless, it should be possible to recognize broad categories as a guide to further investigation.

3.3.1. Definitions

The following definitions are proposed (Table 3.2).

Duricrust: an indurated product of surficial and pene-surficial processes formed by cementation or replacement of bedrock, weathering deposits, unconsolidated sediments, soil or other materials produced by low-temperature physico-chemical processes.

Silcrete: an indurated deposit mainly consisting of silica (SiO_2), which may be formed by lateral or vertical transfer and which may include pedogenetic, groundwater or leached varieties. Subdivisions may be made on the basis of the dominant fabric type. Commonly they are poor in Fe, Al, Ca, K, Mg and P. Subdivisions may also be made on the basis of the dominant fabric type (Langford-Smith 1978; Summerfield 1978, 1983).

Calcrete: an indurated deposit mainly consisting of Ca, Mg carbonates. The term includes non-pedogenetic forms produced by fluvial or groundwater action; they may be pedogenetic by lateral or vertical transfer. Subdivisions are usually made on the basis of degree and type of cementation (e.g. powder, nodular, concretionary).

Gypcrete: an indurated deposit mainly consisting of calcium sulphate dihydrate. The main subdivisions are based on the degree and type of induration (e.g. powder, laminated) but also include desert roses in dune sand. It may include non-pedogenetic forms such as blown gypsum dune sand but is normally pedogenetic by vertical transfers (Goudie 1983).

Alucrete: a form of indurated deposit often called 'bauxite (Alucrete) crust', containing Al and Fe in residual laterite deposits. The Al is in sufficient quantity to be of commercial use. It may be subdivided on the basis of degree and type of induration. It may also be detrital, reworked or pedogenetic.

Ferricrete: a form of indurated deposit consisting of accumulations of sesquioxides, mainly iron, within one or several ferruginous or ferrallitic soil horizons. It may form by deposition from solution, moving laterally or vertically, or as a residue after removal of silica, alkalis, etc (see Chapter 2 for explanatory diagrams). The term 'carapace' is sometimes used for moderate induration and 'cuirrasse' for high induration. It may be pedogenetic by retention or accumulation of minerals and by segregation within vadose profiles. Groundwater forms are pisolitic. Subdivisions are based on degree and type of induration.

Vertisols: dark coloured mature soils, rich in swelling clays strongly bonded to humic compounds. Typically they show deep mixing by vertical movement due to clay volume change and possess large contraction cracks and slickensides; they are also called 'black cotton soils'. The term 'Gilgai' is sometimes used for associated microtopography features.

Fersiallitic andosols: soils, often clays, derived partly or wholly from volcanic deposits and often dark coloured, essentially amorphous allophane-humus complexes. They have an enormous water-holding capacity which exceeds 100% and can reach 200% in hydromorphic tropical andosols, but prolonged desiccation can lower this capacity, often irreversibly. They have high exchange capacity and are very clay and iron rich; they indurate on drying.

Fersiallitic soils (*sensu stricto*): soils with some reddening. 2:1 clays are dominant by both transformation and neoformation and the cation exchange capacity of the clays is greater than 25 mEq/100 g. Where vertical development is incomplete they form brown fersiallitic soils; where complete, saturated or almost saturated complex, red fersiallitic soils and when complex, desaturated and degraded, acid fersiallitic soils (see Chapter 2 for details of occurrence and Table 3.2 for subdivisions).

Ferruginous soils (*sensu stricto*): soils intermediate between those formed by fersiallitization and ferrallitization. Weathering of primary materials is stronger than in fersiallitic soils but not as pronounced as in ferrallitized soils. There is some removal of soluble silica by drainage. Neoformed clays are usually kaolinitic but some 2:1 clays persist; lessivied gibbsite is absent. Horizons are often in the form of a kaolinitic saprolite, and the development is strongly influenced by age.

Ferrallitic soil (*sensu stricto*): final phase of development of thick soil profiles in hot, humid climates in which most primary minerals, even quartz, are affected by total hydrolysis. Oxides of iron, aluminium, silica and bases are liberated but iron and aluminium are retained in the profiles while the bases and some silica are removed in solution; neoformed kaolinites are poor in silica. Main characteristics are quartz, kaolinite, gibbsite, haematite or goethite. An argillic horizon is generally absent.

3.4. Classification for engineering purposes

Traditional geotechnical classification schemes generally have been developed to assess the engineering behaviour of temperate soils. These soils are often little altered sedimentary or transported deposits and in the majority of cases their engineering behaviour can be predicted from schemes based on plasticity and grading characteristics measured in standard laboratory tests. For tropical residual soils, however, engineering behaviour cannot be so easily predicted because:

(a) The weathering products that result under certain tropical conditions may contain minerals with unusual properties.

(b) Weathering of a material in situ implies the presence of a relict structure which may persist as a form of weak bonding even in the most extremely weathered products. Such a bonding can influence metastable behaviour. Under certain engineering applications relict structures may also determine joint block failure patterns throughout the history of a slope.

These factors raise many doubts as to the reliability of conventional laboratory tests in predicting behaviour under field conditions. Early recognition is important so that appropriate tests may be properly employed (see Chapter 5 and 6). A different approach to geotechnical classification is therefore recommended for tropical residual soils.

For these reasons it was decided that the formal French classification (Table 3.2) should be adopted for the Working Party Report. As already stated, weathering products depend on the mineralogy of the parent materials, on the nature of the tropical climate and on the drainage conditions. In addition, special groups may derive from certain volcanic materials, particularly where they are found at altitude and hence the higher elevation has a modifying influence on temperatures. The importance of recognizing the interaction of these factors for engineering classification is that the groups of secondary minerals which form the basis of the pedogenetic classifications are all characteristic of distinct geotechnical behaviour.

3.4.1. The tropical weathering process

Tropical weathering profiles have been represented in engineering terms by a gradational series of weathering zones (Fig. 1.1) passing from fresh rock at depth to the most intensely weathered material (residual soil) at ground surface (Lumb 1962; Geological Society Engineering Group Working Party Report 1977).

Within this weathered profile certain general divisions may be made. Above the fresh 'bedrock' (Grade I) the slightly weathered and moderately weathered zones (Grades II and III) tend to behave in engineering terms as rock and have been defined in this Report as 'weathered bedrock'. In the highly weathered zone (Grade IV) and above the material tends to behave in engineering terms as a soil. Grades III and IV represent an important transition zone in terms of engineering behaviour; the change from a rock, in which behaviour may be controlled by movement along discontinuities, to a soil where behaviour is controlled by mass deformation. The role of discontinuities is particularly influenced in the tropical regime by the presence of altered material as a coating. Becker (1985) defined 'saprolite' as that part of the weathered mantle (behaving as a soil in engineering terms) which exhibits textural and structural features of the parent rock to the extent that identification of the parent rock could still be made. This is defined here as applying to Grades IV and V. In Grade VI all semblance of original texture and structure has been lost. This Grade includes the pedological soil horizons A and B. For the reasons stated in Chapter 1, tropical residual soil is defined in this Report as Grades IV, V and VI.

The use of these terms is illustrated in Fig. 3.1; for comparison the general teminology of the adopted scientific classification of residual soils given in this Report is also shown.

The weathering profile referred to above is necessarily idealized and this point cannot be too strongly emphasized. In tropical climates extremes of temperature and rainfall abound and soil movement by landslip and water transport is widespread. A residual soil profile can develop on any parent material, including fully formed in situ weathering profiles developed in a transported 'parent' material, such as a river terrace deposit. It may not be unusual, therefore, to encounter one weathered profile grading into a transported soil, which in turn rests on an horizon representing an old erosion surface within a second weathered profile.

Concretionary products are a significant component of tropical residual soils and may be encountered as relatively immature products behaving as a 'soil' in the engineering sense, or in maturity as duricrusts which behave in the engineering sense as a 'rock'. Duricrusts also appear and are often more

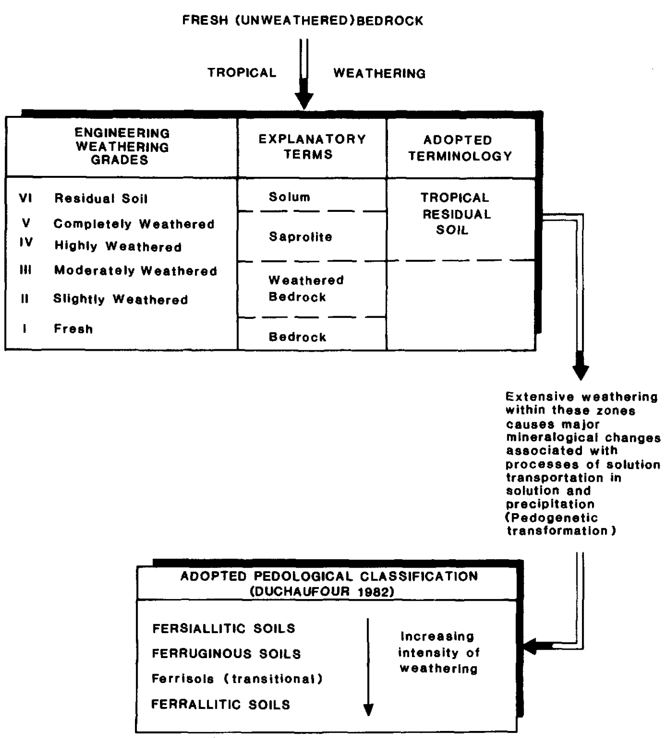


FIG. 3.1. Commonly used terms and adopted pedological classification (Duchaufour 1982).

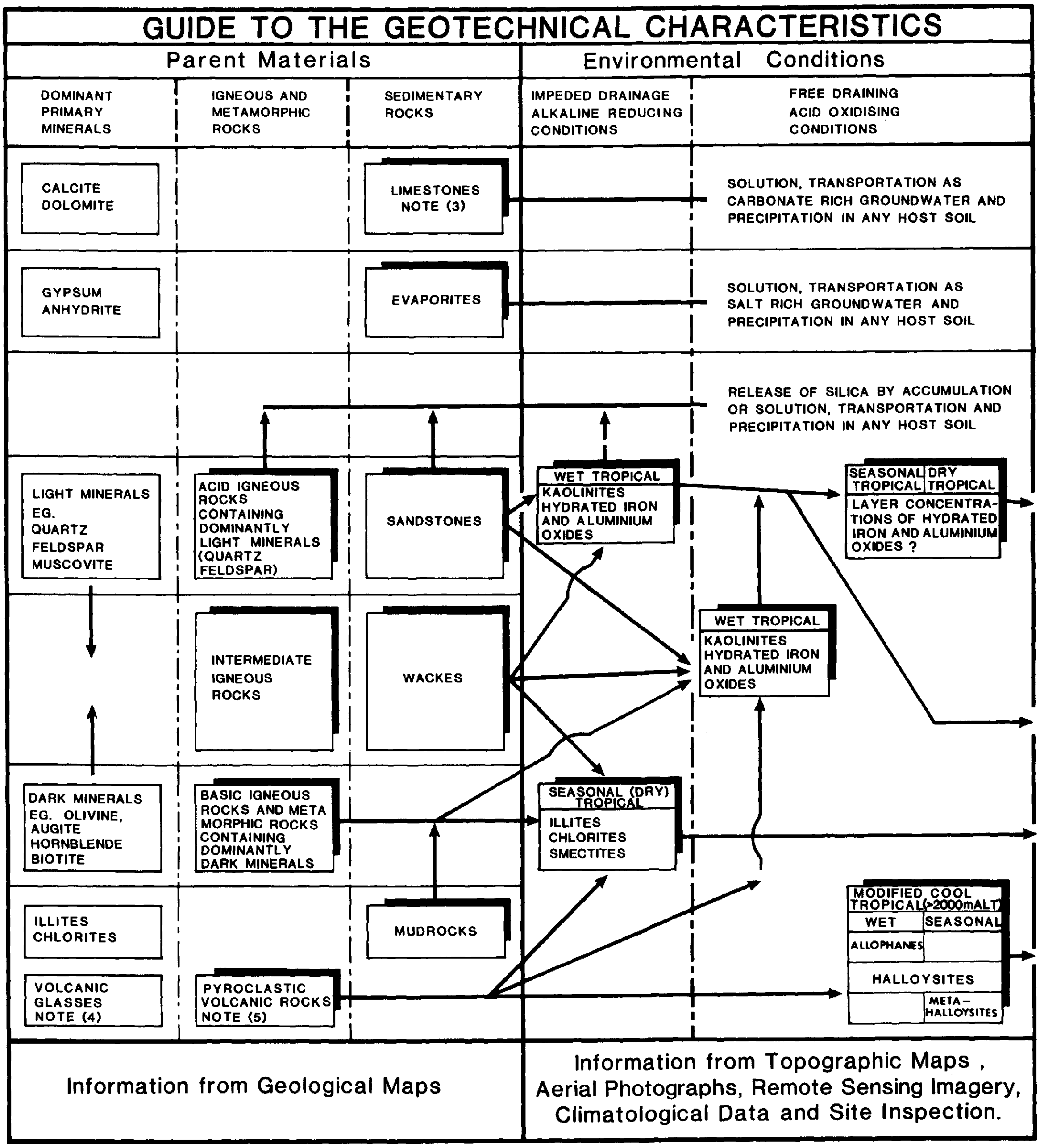
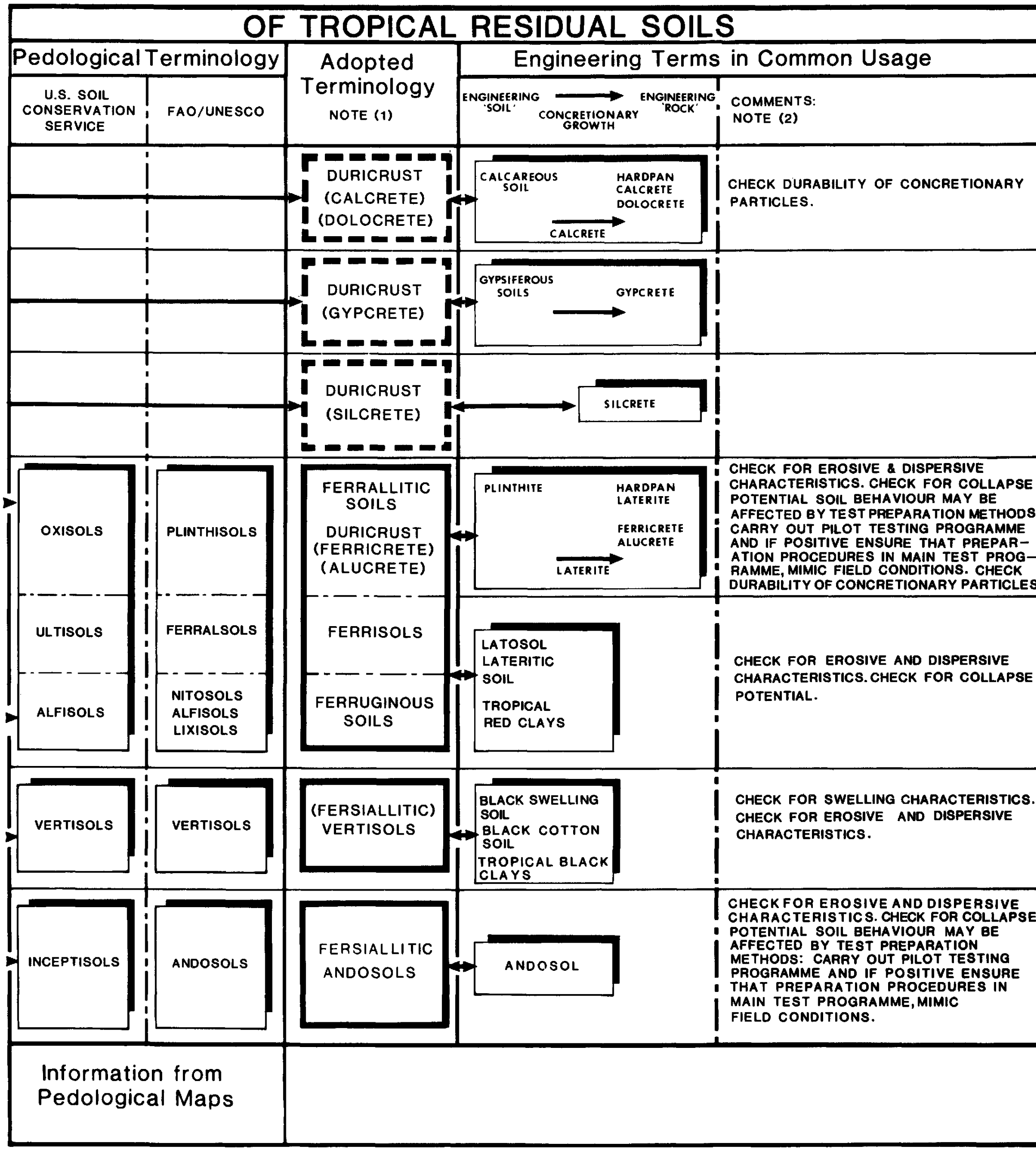


FIG. 3.2. Guide to the geotechnical characteristics of tropical residual soils.

General: The figure is intended for general guidance to assist the prediction of the potentially most likely soil group to be found under any particular combination of parent materials and environmental conditions. Many parent materials and environmental conditions exist as gradational or intermediate phases between those shown. The principles implied in the figure should be applied in such situations.

Note (1): These terms should be used as qualifying terms to support a full and detailed soil description (Chapter 4) e.g. Firm dark grey–brown slightly silty CLAY with occasional rootlets and fine gravel-size calcareous nodules (VERTISOL).



Note (2): The notes in the final column are intended as an early indication of typical behavioural characteristics associated with certain soil groups. Detailed discussion of laboratory testing procedures and engineering behaviour is given in Chapters 5 and 6.
Note (3): The flowpath indicated relates to pure limestones which pass into solution and leave a residual karst landscape.
For impure limestones (e.g. argillaceous) the reader should also refer to flowpaths from the appropriate primary minerals.
Note (4): Volcanic glasses may include dark minerals such as olivine, augite, hornblende and biotite.
Note (5): Other extrusive volcanic rocks are included under acid, intermediate or basic igneous rocks, as appropriate.

dominant in non-tropical environments although they are the product of a pedogenetic process often initiated under tropical conditions. For completeness, therefore, duricrusts must also be included in this discussion (see Chapter 2 and Section 3.3.1, above).

3.4.2. Recognition of geotechnical characteristics

The flow chart in Fig. 3.2 suggests that geotechnical characteristics may be predicted by accessing existing sources of information. It is intended to provide general guidance to predicting the soil groups most likely to be found under any particular combination of parent materials and environmental conditions. This system of prediction may begin at the feasibility stage using the procedures described in Chapter 4.

(i) *Parent materials*. Acid igneous and metamorphic rocks, together with sandstones of sedimentary origin, are composed dominantly of quartz and feldspars. As quartz is very resistant to weathering it has an important role in influencing the texture of the secondary products by remaining as quartz particles while silica in solution can lead to the formation of silcrete duricrusts. Feldspars either slowly weather to clay minerals of the kaolinite group or release hydrated oxides of aluminium and small amounts of iron.

Basic igneous and metamorphic rocks are composed dominantly of minerals such as biotite mica, amphiboles, pyroxenes and olivines, which weather initially to clay minerals of the smectite group. This general statement may be misleading however as the exact processes depend on climatic and other local characteristics. Mudrocks of sedimentary origin generally contain illites, chlorites or smectites.

Extrusive volcanic rocks, when associated with cooler tropical climates experienced at altitude, can produce allophanes, halloysites or metahalloysites.

Evaporites dissolve readily to release the soluble sulphates which can lead to the development of gypcrete.

Limestones and other carbonate-rich rocks readily dissolve to produce carbonate-rich groundwater, which in certain conditions can lead to the development of calcrete or dolocrete duricrusts (Netterberg 1969, 1971, 1983).

(ii) *Environmental conditions*. The information from geological maps should be supplemented by an assessment of the environmental influences on the weathering process. Topographic maps, aerial photographs and remote sensing imagery provide information on present slope angles, site elevation, drainage conditions and morphological history. A site reconnaissance is particularly recommended for example to assess whether the specific site is affected by erosion so that weathering profiles may be of limited thickness. Conversely, a more stable site may comprise deep weathered profiles.

Climatological data such as annual rainfall, mean annual temperature and length of the dry season are also important. Every effort should be made to describe the area in terms of three fundamental climatic groupings; wet tropical, seasonal (dry) tropical or cool tropical at altitude. For duricrusts, it is important to note that seasonally dry conditions are an essential criteria for full development.

In locations where profile drainage is impeded, reducing conditions dominate and initial weathering products such as smectites and chlorites remain dominant within vertisol profiles. Where oxidizing conditions prevail, generally on slopes between 10 and 30° and where adequate throughflow of water occurs, the smectites which originate from basic rocks change to kaolinite group minerals and the hydrated oxides of iron and aluminium are released. These minerals dominate the ferruginous soil profiles, which develop under stronger weathering to ferrisols and ultimately to ferrallitic soils. Progressively stronger weathering results in increasing amounts of the hydrated oxides of iron and aluminium. The process is encouraged in areas of high rainfall by strong leaching. When periods of high rainfall are separated by a dry season, concentrations of the hydrated oxides may develop as layers within the ferrallitic soil profiles.

(iii) *Pedogenic information*. Where pedological survey data is available this should also be referenced. The Duchaufour system tends to be limited in geographical coverage to those areas of the world that have developed historically under French influence. At least two other classifications are used widely, those of the US Soil Conservation Service and the FAO/UNESCO system. To enable use of data based on these systems, Fig. 3.2 contains a summary of their general terminology which is related to the classification adopted in this Report; appropriately highlighted in Fig. 3.2.

(iv) *Engineering terminology*. The engineering literature often describes tropical soils under two general categories; the tropical black soils and the tropical red soils. Whilst this may be a useful first approximation, there can be confusing overlap in detail and it is recommended the engineer should refer to the indicators given in the flow chart (Fig. 3.2).

The black tropical soils found in vertisol profiles are generally described in the engineering literature as black cotton soils, black swelling clays or tropical black clays. Local terms such as negur, mbuga, adobe or vlei soils may also be used.

There is considerable confusion in the engineering literature over the use of terms for the so called 'red' tropical soils, i.e. those soils contained within the ferruginous, ferrisol and ferrallitic soil profiles. Only a small proportion of sesquioxides will impart a red coloration and any red soil has tended to be termed a laterite. Such generalized usage should be avoided. In engineering terms it is particularly important to recognize different types of red soils because they contain different amounts of iron and aluminium oxides which possess unusual properties and thus have important effects on the geotechnical properties of the soils in which they are a major component.

Nogami (1985) described the group 'tropical red soils' (undifferentiated) as lateritic soils rather than laterite and suggested that strictly this term should only be applied to those soils that behave predictably in standard laboratory tests. However, as the hydrated oxides become more concentrated they have an increasing effect on engineering properties. Where these minerals become concentrated into discrete horizons such layers have been called plinthite and probably coincide with the original laterite defined by Buchanan (1807) as a red tropical soil which hardens on exposure to air. Under conditions caused by long term changes in climate, drainage or landform, such horizons can harden to a ferricrete or alucrete duricrust. These concretionary layers have also been termed laterite in the literature.

Charman (1988) attempted to clarify the confusion over the term laterite by recognizing a cycle of concretionary development from an original plinthite layer to a mature hardpan-laterite. This recognizes intermediate duricrust forms of nodular laterite and honeycomb laterite.

In view of this confusion the Report recommends that the formal classification shown in Fig. 3.2 be adopted. The general parallels to engineering terms in common use should assist.

(v) *Classification and engineering behaviour.* The engineering behaviour of tropical residual soils is described in Chapter 6. Each of the main groups has certain behavioural characteristics which are quoted to demonstrate the utility of the proposed classification.

In the vertisols group, behaviour is dominated by the volume changes exhibited by smectite clay minerals when they are subjected to changes in natural moisture content. This behaviour is described in detail in Chapter 6. Several methods of prediction of swelling potential are available, based on the results of index tests; they are described in Chapter 5.

In the ferruginous, ferrisol and ferrallitic soil groups variable quantities of sesquioxides affect the results of standard laboratory tests in several ways (see Chapter 5):

Aggregation of clay-size particles. The sesquioxides within the fine fraction of tropical soils coat the surface of individual soil particles because of the electrical bonding between the negatively-charged kaolinite and the positively charged hydrated oxides. The coating reduces the ability of the clay minerals to absorb water and can also physically cement adjacent grains, thus producing aggregates of increased size. Both factors reduce plasticity, but intensive remoulding of the soil breaks down aggregates and the sesquioxides coatings, with an attendant increase in plasticity. This is important when relating laboratory testing procedures to construction operations. Field operations of excavation, transport and placement are unlikely to break down the fine soil aggregates to the extent that plasticity is affected. The degree of working required to prepare laboratory specimens for Atterberg limit determinations is, by comparison, very much greater. The plasticity of the construction material may thus be lower than would appear from the standard Atterberg or other laboratory tests on remoulded samples.

Irreversible changes in plasticity on drying. Soils which contain hydrated oxides of iron and aluminium may become less plastic i.e. exhibit lower Atterberg limit values on drying. This is partly because dehydration of the sesquioxides creates a stronger bond between the particles, which resists penetration by water. The process cannot be reversed by re-wetting. The effect is observed during air-drying but is more pronounced on oven-drying at higher temperature.

Loss of water of hydration on drying. The water of hydration in the sesquioxides of iron and aluminium may be driven off by oven-drying at 105°C, the standard temperature for testing temperate region soils. This water normally takes no part in the engineering performance of the material but is reflected in the results of tests undertaken to temperate standards at a higher moisture content.

Collapse characteristics or decrease in volume upon addition of water and with no addition of load. Susceptible rocks have high void ratios but relatively low moisture content and hence they may be identified by determining whether the natural void ratio is higher than the void ratio at the liquid limit. This indicates a soil that is susceptible to changes in structure with saturation. Another method, used by Jennings (1965), makes use of the consolidation test. These matters are more fully described in Chapters 5 and 6.

The fersiallitic andosols contain allophanes together with halloysites and metahalloysites of the kaolin group. These minerals also influence engineering behaviour.

Soils containing metahalloysite possess aggregations of clay particles which can be dispersed by manipulation during testing. Aggregates may be reformed unless the soil is oven-dried at 105°C, which removes all interparticle water and collapses the aggregated structure.

Soils containing hydrated halloysite lose water of hydration or water on drying. This occurs when the relative humidity falls below 50% or the temperature rises above 50°C. The loss of water of hydration in a pure halloysite is equal to 14% of the dry soil weight. Drying causes aggregates to form and the soil then behaves like the metahalloysite described above.

Soils containing amorphous allophane form aggregates on drying. This is an irreversible process caused by loss of interparticle water and water from the amorphous clay mineral and is accompanied by large reductions in porosity. The effect can be so marked as to change the soil from a 'clay' to a 'sand'.

Clearly, the properties described above render the soil behaviour susceptible to the methods used to prepare specimens for laboratory tests. Early identification of such behaviour is necessary and a pilot testing programme should be carried out (as described in Chapter 5) to determine the need for modification of standard test procedures.

Duricrusts provide a unique problem to the engineer because they do not necessarily represent a material that behaves as a 'rock' in the engineering sense. They are essentially concretionary particles in a host soil, as a honeycomb structured material of coalesced concretionary particles or as an indurated horizon. In any event they exhibit variable engineering properties within a deposit and require detailed description (see Chapter 4), evaluation and quality control. Particular care should be given to the evaluation of particle strength; unless fully mature duricrusts may be relatively weak and hence considerably be changed by handling and processing.

4. Field description and identification

4.1. Introduction

This Chapter defines a framework for the field description of tropical residual soils which is compatible with the classification previously proposed. This is done largely by use of tables and by reference to key publications. Only brief comment is made on the methods and procedures used to obtain data for field description.

Sections 2.4 and 2.6 of Chapter 2 indicated the factors governing the development and formation of tropical residual soil types. Chapter 3 related residual soils to potential engineering behaviour. Field identification of these soils should therefore recognize both these governing factors and the classification characteristics.

Field description may be undertaken using a number of parameters identified as being of relevance in the development and current condition of tropical residual soils. These parameters are subdivided into three principal groups: general site characteristics, soil material characteristics and soil mass characteristics (Tables 4.1, 4.2 and 4.3 respectively).

The methodology for identifying the above characteristics must be adaptable to a wide variety of projects. It is likely that in the field the description of tropical soils will not be made in isolation and that other materials will be found in close association. Therefore any proposed methodology for the field description and identification of tropical residual soils must be compatible with, and capable of integration with, descriptive systems for such other materials. It must be possible to build up a total ground profile which might range from fresh bedrock through weathered bedrock to residual soil, and which might be inter-fingered with, for example, colluvium. These are important practical considerations particularly with respect to the logging of cores or exposed faces. See also the Appendix to the Report, p 86.

4.2. General site characteristics

4.2.1. Location

The location and extent of each site under consideration should be adequately defined. The subdivision of project locations will be governed by the size, stage and type of project, together with naturally occurring boundaries within its area.

4.2.2. Landform

The inter-relationship between tropical residual soil occurrence and landform was discussed and illustrated in Chapter 2. It follows that the identification and classification of landform should be an important element in the field description process. A previous Working Party on Land Surface Evaluation for Engineering Purposes (1982) reviewed and commented on methods for undertaking landform definition.

Although the scale and methods of defining landform may be a function of project size and type, the overall objective may best be achieved by use of currently utilized methods of terrain analysis (Mitchell 1973) in which, for instance, land systems may be defined in terms of their component facets and elements. Such an approach may aid in the effective organization of projects into relevant site or soil mass subdivisions. Based on land classification and terrain evaluation, it has the advantage of enabling information on soils to be transferred to other areas of similar geology, topography and climate.

Remote sensing, including the use of air photo interpretation and satellite imagery, provides a powerful tool for terrain evaluation and is especially important in areas where field mapping is limited.

Field procedures for terrain analysis involve the definition and mapping of site morphology; Table 4.1 indicates relevant definitions which may be utilized for the purpose. Figure 4.1 (Cooke & Doornkamp 1974) illustrates a typical end product of morphological mapping. Tables 4.4 and 4.5 and Figs 4.2 and 4.3 indicate how landform may be defined in terms both of relief and slope.

4.2.3. Geology

It was established in Chapter 2 that bedrock geology can have a significant influence on the development and nature of tropical residual soils. The nature of parent material frequently has a close relationship with landform in its influence on tropical residual soils; indeed variations within the bedrock geology may affect the engineering significance of the resulting residual soil (Irfan 1988).

The relevant bedrock geology may be defined in simple terms (Table 4.6) by use of material adapted from BS5930 or from the Working Party Report on the Mapping of Rock Masses (1977). This does not preclude a more detailed description of the geology if

TABLE 4.1. *General site classification*

Parameter	Classification	Procedure/Reference
Location	Position Boundaries Elevation Site extent	Use local/national grid/available co-ordinates or refer to physical boundaries. Use local/national survey system. Size of each site dependent on type and scale of project.
Landform	Relative relief Slope angle Profile form Plan form	Scale and type of project will govern amount of detail and methodology. Example, Fig. 4.2, use Tables 4.4 and 4.5, also Figs 4.3 and 4.4.
Geology	Bedrock type	Table 4.6 adapted from BS5930, with additional information if available.
	Information source	Note whether from field mapping, literature search, test pit, borehole.
	Tectonic history	Outline seismicity and tectonic stability.
Current climate	Annual rainfall Rainfall variations Temperature variations Humidity Evapo/transpiration	Information to be gathered by actual measurement or from records. General climatic groupings (Table 4.7).
Hydrology	Streams/rivers Bed maturity Water table	Note occurrence, general pattern (Table 4.8), flow (Table 4.9). Record position, variations and responses to rainfall.
Vegetation	Type Percentage cover	Natural and imposed, in broad terms (Table 4.10).

TABLE 4.2. *Soil material characteristics*

Parameter	Classification	Procedure/reference
1. Moisture	State	Estimation, Jennings *et al.* 1973, Table 4.11. Also rate of change in response to wetting/drying.
2. Colour	Colour chart	American Geological Society
3. Strength	Cohesive soil	Table 4.12. Use hand vane, penetrometer or probe to gauge classification.
	Non-cohesive/cemented soil Rock-like/indurated	Table 4.13 Table 4.14. Use field or Schmidt hammer to aid classification.
4. Fabric	Origin Voids Orientation Distribution Fissuring	Formed or inherited, Table 4.15 Amount (porosity) Table 4.16 Particle orientation pattern, Table 4.17 Table 4.18 Orientation, spacing, condition
5. Texture	Particle size Particle shape Grading	Table 4.19 (BS5930). Use guidance charts for size and shape. Table 4.20 Estimation aided by simple sieving, Table 4.21
6. Density and relative density	Bulk undisturbed Remoulded	Field estimation Table 4.22 Field estimation, note ratio
7. Apparent behaviour	Remoulded strength Durability Infiltration Swell/shrink Plasticity	As for density above. Note ratio. Field slake test, Table 4.23 Field infiltration test Field wetting/drying tests Field estimation, Table 4.24
8. Mineralogy	Primary Secondary	Hand lens examination. Carbonate test, Table 4.25. Note in particular quartz, feldspar, and ratio of primary to secondary. Table 4.26
9. Classification	Type	Based on proposed classification or unique project system.

TABLE 4.3. *Soil mass characteristics*

Parameter	Classification	Procedure/Reference
Composition	Materials Geometry Nature	List material types, construct section. Record boundaries, extent, shape of soil mass. Borrow pit, hillslope, road cutting etc.
Structure	Layering Jointing Faulting Slickensiding Contacts	Discontinuity spacing defined by Table 4.27. Nature of discontinuity surfaces described as per ISRM standards (Anon 1977); attitude defined as dip/dip direction. Type and nature of material contacts, Table 4.28. Relationship of material types.
Behaviour	Erodibility Slope angles Slope failure Strength	By observation. Nature of erosion. Measurement of both natural and cut-slope angles. Note mode and history of failure. Note response to imposed loads both in construction and in in situ testing programmes.
Nomenclature	Profile/mass	Based on proposed classification of Chapter 3.

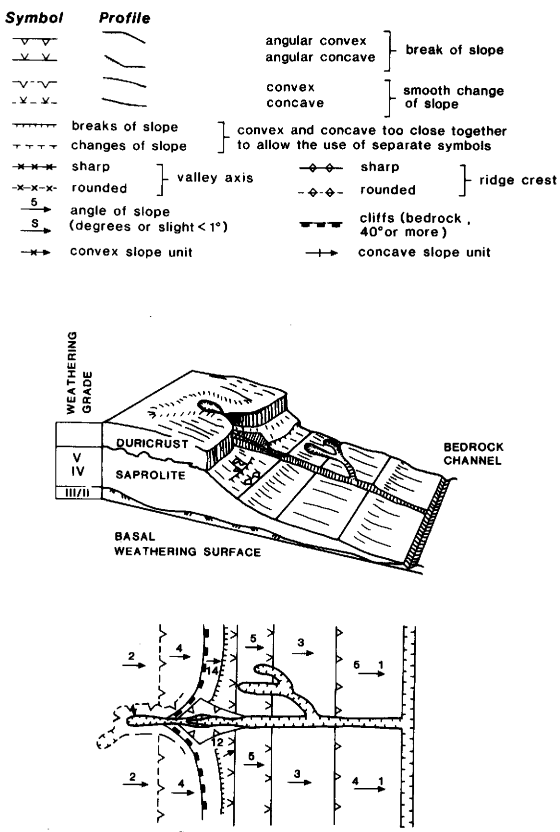


FIG. 4.1. A typical end product of morphological mapping (after Cooke & Doornkamp 1974).

required. In conjunction with bedrock identification, the geological history and particularly the tectonic maturity of the site should be established.

TABLE 4.4. *Landform; relative relief*

Class	Relative relief (m)	Term
1	<10	Very low
2	10–30	Low
3	30–100	Moderate
4	100–300	High
5	>300	Very high

(after Young 1976)

TABLE 4.5. *Landform; slope angles*

Class	Angle (degrees)	Term
1	0–2	Level to very gentle
2	2–5	Gentle
3	5–10	Moderate
4	10–18	Moderately steep
5	18–30	Steep
6	30–45	Very steep
7	45–70	Precipitous
8	70–90	Subvertical

(after Young 1976)

4.2.4. Current climate

Climate should be described in terms both of the general governing conditions (Table 4.7) and the current and immediately preceding weather. The climatic description should be capable of quantifying annual rainfall (including intensities), seasonal and diurnal rainfall variations, seasonal and diurnal temperature variations, and humidity.

Determining the local evaporation/transpiration ratios should be an end product of site climatic observations. For some projects it may prove useful to

TABLE 4.6. *Aid to identification of rocks for engineering purposes*

Grain size, mm	Bedded rocks (mostly sedimentary): Grain size description		At least 50 % of grains are of carbonate	At least 50 % of grains are of fine-grained volcanic rock		Obviously foliated rocks (mostly metamorphic): Grain size description		Rocks with massive structure and crystalline texture (mostly igneous)	Grain size description					Grain size (mm)
More than 20 20 6 2	RUDACEOUS	CONGLOMERATE Rounded boulders, cobbles and gravel cemented in a finer matrix Breccia Irregular rock fragments in a finer matrix	LIMESTONE and DOLOMITE (undifferentiated) Calcirudite	Fragments of volcanic ejecta in a finer matrix Rounded grains AGGLOMERATE Angular grains VOLCANIC BRECCIA	SALINE ROCKS Halite Anhydrite	COARSE	GNEISS Well developed but often widely spaced foliation sometimes with schistose bands Migmatite Irregularly foliated: mixed schists and gneisses	MARBLE QUARTZITE Granulite HORNFELS Amphibolite Serpentine	COARSE	GRANITE[1] Pegmatite These rocks are sometimes porphyritic and are then described, for example, as porphyritic granite	Diorite[1,2]	GABBRO[3]	Pyroxenite Peridotite	More than 20 20 6 2
0.6 0.2 0.06	ARENACEOUS Coarse Medium Fine	SANDSTONE Angular or rounded grains, commonly cemented by clay, calcitic or iron minerals Quartzite Quartz grains and siliceous cement Arkose Many feldspar grains Greywacke Many rock chips	Calcarenite	Cemented volcanic ash TUFF	Gypsum	MEDIUM	SCHIST Well developed undulose foliation; generally much mica		MEDIUM	Microgranite[1] These rocks are sometimes porphyritic and are then described as porphyries	Microdiorite[1,2]	Dolerite[3,4]	—	0.6 0.2 0.06
0.002 Less than 0.002	ARGILLACEOUS	MUDSTONE / SILTSTONE Mostly silt SHALE Fissile / CLAYSTONE Mostly clay	Calcareous mudstone Calcisiltite Calcilutite CHALK	Fine-grained TUFF Very fine-grained TUFF		FINE	PHYLLITE Slightly undulose foliation; sometimes 'spotted' SLATE Well developed plane cleavage (foliation)		FINE	RHYOLITE[4,5] These rocks are sometimes porphyritic and are then described as porphyries	ANDESITE[4,5]	BASALT[4,5]	—	0.002 Less than 0.002
Amorphous or crypto-crystalline		Flint: occurs as bands of nodules in the Chalk Chert: occurs as nodules and beds in limestone and calcareous sandstone			COAL LIGNITE		Mylonite Found in fault zones, mainly in igneous and metamorphic areas			Obsidian[5]	Volcanic glass			Amorphous or crypto-crystalline
		Granular cemented-except amorphous rocks				CRYSTALLINE				Pale ← colour		→ Dark		
		SILICEOUS	CALCAREOUS	SILICEOUS	CARBONACEOUS	SILICEOUS		mainly SILICEOUS		ACID Much quartz	INTERMEDIATE Some quartz	BASIC Little or no quartz	ULTRA BASIC	

SEDIMENTARY ROCKS
Granular cemented rocks vary greatly in strength, some sandstones are stronger than many igneous rocks. Bedding may not show in hand specimens and is best seen in outcrop. Only sedimentary rocks, and some metamorphic rocks derived from them, contain fossils.
Calcareous rocks contain calcite (calcium carbonate) which effervesces with dilute hydrochloric acid.

METAMORPHIC ROCKS
Most metamorphic rocks are distinguished by foliation which may impart fissility. Foliation in gneisses is best observed in outcrop. Non-foliated metamorphics are difficult to recognize except by association. Any rock baked by contact metamorphism is described as a 'hornfels' and is generally somewhat stronger than the parent rock.
Most fresh metamorphic rocks are strong although perhaps fissile.

IGNEOUS ROCKS
Composed of closely interlocking mineral grains. Strong when fresh; not porous
Mode of occurrence: 1. Batholiths; 2. Laccoliths; 3. Sills; 4. Dykes; 5. Lava flows; 6. Veins

This table is intended as a guide only.
Principal rock types are shown in bold capitals. The boundaries of the heavy lined box describe the conditions to which the rock name applies.
The table is reproduced from BS 5930:1981 with permission of the BSI. Complete copies of the BS can be obtained by post from BSI sales, Linford Wood, Milton Keynes, MK14 6LE, UK.

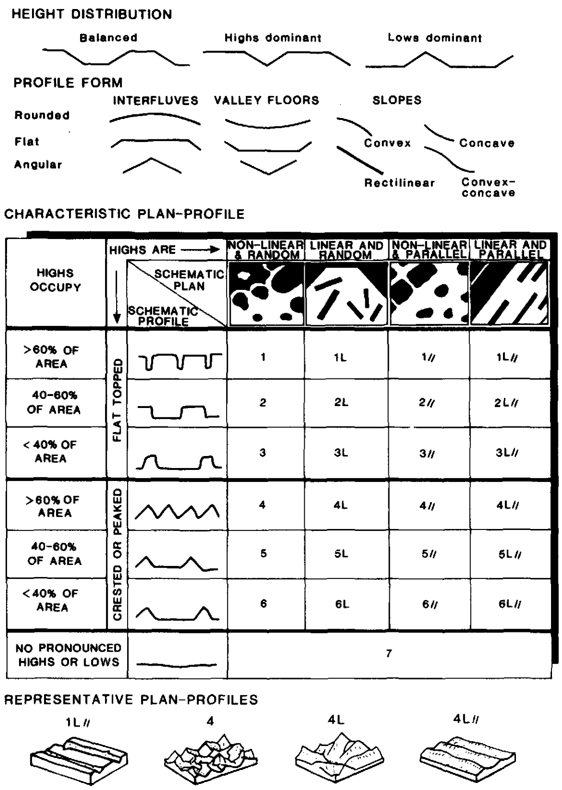


FIG. 4.2. Landform definitions.

establish local climatic indices on the lines described by Weinert (1974). This climatic index is given by

$$N = 12\,Ej/Pa$$

where Ej is the evaporation during the hottest month and Pa is the annual rainfall.

Weinert derived this index for use in southern Africa as an aid to the assessment of road aggregate durability in response to weathering environments. 'N' values less than five are reported as indicating climatic conditions conducive to a residual soil mantle.

4.2.5. Topography and hydrology

As pointed out in Chapter 2, the topography and hydrology of a site will have a major influence on its drainage characteristics, which in turn are known to have a major effect on residual soil mineralogy.

The natural drainage pattern should be defined and described in broad terms (Tables 4.8 and 4.9), although in practice parts may be covered within landform definition. Particular attention should be paid to the occurrence of streams/rivers/seepages, seasonal variations and stream/river bed maturity.

The nature and occurrence of groundwater should be noted. Any information leading to the definition of the governing groundwater flow regime should be recorded, e.g. position of water tables, variation in water tables and response to rain showers/storms (infiltration capacities).

4.2.6. Vegetation

Vegetation should be defined in terms of type, both natural and imposed, and percentage of cover (Table 4.10).

4.2.7. Interaction of landform, geology and climate

An example of the influence and interaction of geology, topography, climate (rainfall) and hydrology (drainage) is remarkably demonstrated on the small island of Dominica in the Caribbean (Rouse *et al.* 1986). Here the geology is relatively constant (volcanic rocks comprising andesitic and dacitic pyroclastics) and the wide variation in topography (0–1000 m), rainfall (1000–7600 mm per annum) and in drainage conditions has led to the formation of four distinct groups of soils which embrace the major part of those included in the classification of residual soils formed over basic igneous rocks. This interaction is illustrated in Fig. 4.3.

4.3. Soil material characteristics

4.3.1. General

It has been considered (Ferreira 1985) that characterization of the decomposed rocks and tropical soils could be made on the basis of morphological characteristics, mineralogical characteristics, identification tests and engineering properties.

Field identification techniques can only partly define some of the above, although indirect measurements or tests may help. The combination of field identification with selective laboratory work should enable a more complete characterization to be achieved. Laboratory testing is discussed more fully in Chapter 5, but for field identification of material characteristics it is necessary to concentrate on the description of visible elements and the recording of available material behaviour.

Current geotechnical description standards for fine grained soils, such as the Unified, AASHO (ASTM D2487 and D3282) or the BSCS (incorporated in BS5930), are dominated either by emphasis on arenaceous material grain size and grain size distribution or by plasticity, as measured by Atterberg limits (Mitchell & Sitar 1982; Child 1984). To rely solely on such standards would be misleading in a residual soil and commonly used temperate zone identification and classification systems may be difficult to apply to tropical soils for engineering prediction.

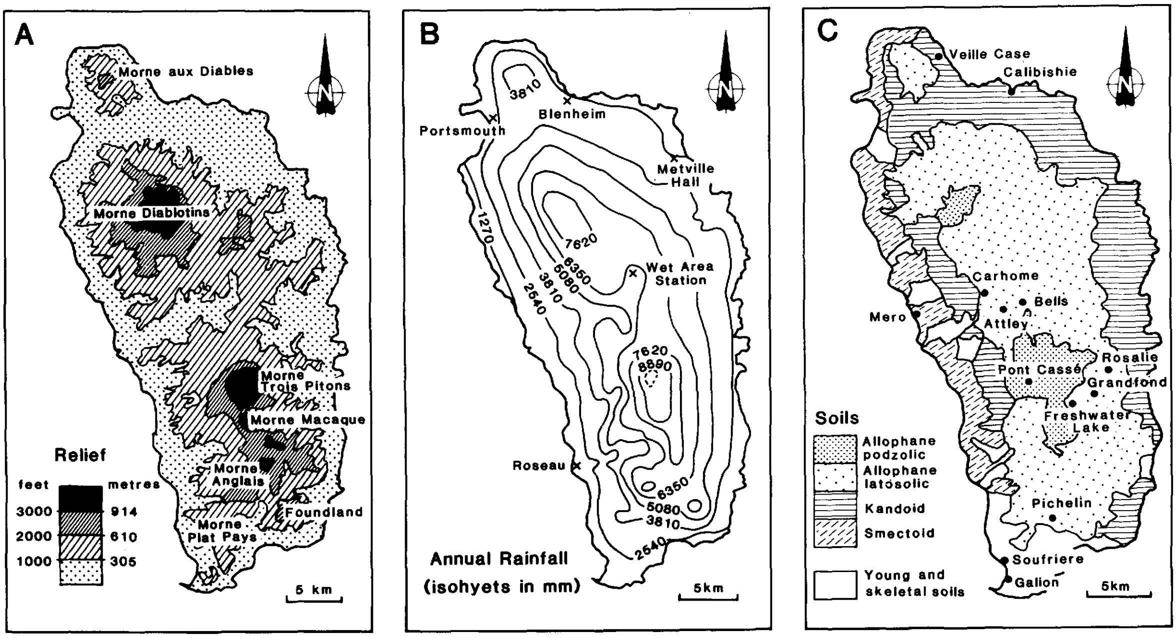


FIG. 4.3. Dominica: relief, rainfall and soils. This figure is reproduced from 'Volcanic soil properties in Dominica, West Indies' by W. C. Rouse, A. J. Reading and R. P. D. Walsh, with permission of the publishers, Elsevier Science Publishers, B. V. Amsterdam. The article appeared in *Engineering Geology* **23** (1986) 1–28.

Nevertheless, the above standard descriptions contain elements which may be significant within the tropical environment. It is considered that they should form a part of the more broadly based material descriptive framework, as outlined below.

4.3.2. Moisture state

Moisture state may be used both as an aid to identification in some soil types and as an indication of potential behaviour (Table 4.11). The general terms dry, slightly moist, moist, very moist, and wet were suggested (Jennings *et al.* 1973). The apparent moisture state will naturally relate to the soil texture and must therefore be assessed and interpreted with this in mind. In addition to a current moisture state, in some environments it may be of significance to assess its variation with time and its response to climatic variation.

4.3.3. Colour

Colour is given a much greater significance than is usual with temperate soils. Colour may frequently be an index to chemical or mineralogical change (Hodgson 1976) and the use of colour charts in the field is strongly recommended. The 'Rock-Color Chart' produced by the Geological Society of America is relatively inexpensive and very compact. Such charts should be used not only to describe the predominant colour but also secondary mottling. Where possible colour should be noted when the soil is both dry and wet.

4.3.4. Strength

Consistency or strength, both natural and remoulded, should be described using standard definitions for both soil and rock materials (BS5930; Weltman & Head, 1983). The definitions to be used are those relevant to an engineering context (Tables 4.12–4.14). Other detailed strength definitions exist which are primarily of use in pedological work but they may cause confusion in relation to existing geological standards (Hodgson 1976). In pedogenic materials it may be important to describe the strength both of nodules and matrix.

4.3.5. Fabric

Fabric is the physical constitution of the soil as expressed by the spatial arrangement of the solid particles and associated voids (Brewer 1968). In the context of fieldwork this is confined to those features which may be readily inspected by the naked eye or by means of a hand lens. In a residual soil environment the range in scale of 'particles' may be great, from discrete and compound grains to large core-stones.

TABLE 4.7. *Climatic groupings*

A. Low-latitude climates	
Wet equatorial	
Precipitation:	High, 1500–2500 mm/yr, monthly variation 75–25 mm
Temperature:	Mean annual, 24–27°C, range 21–32°C with 1–2°C variation. Diurnal range 8–11°C.
Features:	High temperatures and high precipitation.
Trade wind littoral	
Precipitation:	1500–3000 mm/yr, monthly variation 25–700 mm. Marked summer maximum.
Temperature:	Mean annual 24–27°C, range 18–32°C. Diurnal range 11–14°C.
Features:	Strong winds, cool dry winter.
Tropical desert	
Precipitation:	10–100 mm/yr.
Temperature:	Mean annual 21–27°C, range 1–54°C. Diurnal range 14–17°C.
Features:	Very low rainfall, often in heavy showers.
West coast desert	
Precipitation:	<250 mm/yr, generally virtually nil.
Temperature:	Mean annual 18–23°C, range −1–55°C. Diurnal range 15–20°C.
Features:	Extremely dry, but relatively cool. Small annual temperature range.
Tropical wet–dry climate	
Precipitation:	1000–1700 mm/yr, monthly variation 0–350 mm, marked summer maximum.
Temperature:	Mean annual 24–27°C, range 16–38°C. Diurnal range 8–17°C.
Features:	Marked seasonal contrasts.
B. Middle–latitude climates	
Humid subtropical	
Precipitation:	750–1600 mm/yr, monthly variation 50–175 mm, distinct summer maximum.
Temperature:	Mean annual 16–21°C, range −4–38°C. Diurnal range 5–11°C.
Features:	Moderate annual precipitation, occasional frosts, hurricanes, typhoons.
Marine west coast	
Precipitation:	500–2500 mm/yr, monthly variation 25–100 mm.
Temperature:	Mean annual 7–13°C, range −4–24°C. Diurnal range 8–11°C.
Features:	Dull drizzly weather with cool wet summers and mild wet winters. Cyclone storms.
Mediterranean	
Precipitation:	400–800 mm/yr with summer minimum or winter maximum.
Temperature:	Mean annual 12–18°C, range −1–38°C. Diurnal range 14–19°C.
Features:	Hot dry summers, mild rainy winters.
Middle latitude desert	
Precipitation:	10–100 mm, erratic variation.
Temperature:	Mean annual 4–16°C, range −35–43°C. Diurnal range 11–17°C.
Features:	Very wide variation in temperature between winter and summer. Low unreliable precipitation.
Humid continental	
Precipitation:	400–700 mm/yr, monthly variation 75–125 mm, weak summer maximum.
Temperature:	Mean annual 2–7°C, range −35–29°C. Diurnal range 11–17°C.
Features:	Cool moist summers, heavy precipitation, wide annual temperature range.
C. High-latitude climate: not considered	

(after Strahler 1970)

Brewer proposed a system which deals with the fabric analysis in pedological terminology and which may be adapted to the wider context of this Report. This system is based on the concepts of units of organization and layers of organization, which may be too detailed for the majority of engineering geological or geotechnical projects, particularly for identification in the field, hence only an outline of his approach has been presented in the accompanying Tables (4.15–4.18). If necessary, additional fabric analysis may be undertaken using laboratory based techniques (Chapter 5).

Work on the fabric of granite (Baynes & Dearman 1978a, b) indicated an approach to fabric description

TABLE 4.8. *Drainage spacing*

Class	Spacing (m)	Term
1	<100	Very close
2	100–400	Close
3	400–1500	Moderate
4	1500–3000	Wide
5	<3000	Very wide

(after Young 1976)

TABLE 4.9. *Drainage classification*

Class	Name	Comment
1	Dendritic	Indicates uniform materials
2	Rectangular	Implies strong bedrock jointing, thin soil cover
3	Trellis	Strike ridge topography
4	Parallel	Characteristic of outwash areas of low relief
5	Braided	Alluvial areas where sediment load exceeds stream carrying capacity
6	Radial	In isolated hill masses
7	Pinnate	Generally indicates high silt content as in loess or on flood plains
8	Annular	Indicates igneous or sedimentary domes with concentric fractures or escarpments
9	Deranged	Many ponds or lakes, flat landscape
10	Centripetal	A variation of radial, with drainage towards a central point; centre of an eroded anticline or syncline
11	Internal	Indicates highly porous materials or karst conditions
12	Dislocated	Interrupted drainage due to faults or extrusions

(after Mitchell 1973)

TABLE 4.10. *Vegetation cover*

Classification	
Natural	*Imposed*
Boreal forest	Grazing
Coniferous forest	Cereal crop
Deciduous forest	Root crop
Scrub	Orchard
Grassland	
Savannas	
Savanna woodland	
Temperate rain forest	
Tropical rain forest	
Montane vegetation	
Percentage cover	
>75%	Very abundant
25–75%	Abundant
10–25%	Frequent
4–10%	Occasional
<4%	Rare

TABLE 4.11. *Moisture state*

Class	Description
Dry	Lighter in colour than moist state. Sands loose. Silty soil brittle and crushes to dust. Clayey soils tend to be fissured and cannot be crushed in fingers.
Slightly moist	Gradation between dry and moist.
Moist	Moist horizons tend to exhibit range of colour change. Absence of wet or dry characteristics.
Very moist	Gradation between moist and wet.
Wet	Water films visible on grains and peds. Seepage.

(after Hodgson 1974)

TABLE 4.12. *Strength: cohesive soil*

Term	Undrained shear strength (kN/m^2)	Field test
Very soft	<20	Exudes between fingers when squeezed in hand.
Soft	20–40	Easily penetrated by thumb. Moulded by light finger pressure.
Firm	40–75	Penetrated by thumb with effort. Moulded by strong finger pressure.
Stiff	75–150	Indented by a thumb. Cannot be moulded by fingers.
Very stiff	150–300	Indented by thumbnail. Penetrated to about 15 mm with knife.
Hard	>300	Cannot be indented by thumbnail.

(after Weltman & Head 1983)

TABLE 4.13. *Strength: non-cohesive soil*

Term	Field test
Loose	Can be excavated by spade. 50 mm peg can be easily driven. Easily crushed in fingers.
Dense	Requires pick for excavation. 50 mm peg hard to drive. Crushed by strong finger pressure.
Slightly cemented	Pick removes soil in lumps which can be abraded.

(after BS 5930 1981; Weltman & Head 1983)

for a particular rock type. It is likely that particular projects or soil types may require similarly adapted approaches.

4.3.6. Texture

Texture refers to the size and shape of the soil particles (Tables 4.19–4.21). It is suggested that they should be described using the established standard descriptions with respect to grain size and shape (Anon 1979). The interpretation of field estimations of texture must consider the distinctive properties of some residual soil types, e.g. the aggregation of allophanic clay soils to a silty or even fine sandy texture (Wesley 1973; Mitchell & Sitar 1982). The halloysitic clay soils of East Africa with their high iron oxide contents also show this characteristic (Newill 1961).

4.3.7. Bulk density

The undisturbed bulk density of a soil will reflect the soil particles and their structure and as such is a significant and distinctive characteristic of some soil types (Fitzpatrick 1983; Vaughan *et al.* 1988). Even a

TABLE 4.15. *Origin of fabric features*

Origin	Definition
Orthic	Formed in situ by soil forming processes, e.g. nodules, mineral coatings, root channels, peds.
Inherited	Relicts of the parent rock or parent material, e.g. lithorelicts.

(after Brewer 1964)

TABLE 4.16. *Void ratio and porosity*

Term	Void ratio	Porosity (%)
Very high	>1.00	>50
High	1.00–0.80	50–45
Medium	0.80–0.55	45–35
Low	0.55–0.43	35–30
Very low	<0.43	<30

(after IAEG classification, Anon 1979)

TABLE 4.17. *Fabric orientation*

Orientation	Definition
Strong	>60% of the particles are oriented with their principal axes within 30° of each other.
Moderate	40–60% of the particles are oriented with their principal axes within 30° of each other.
Weak	20–40% of the particles are oriented with their principal axes within 30° of each other.
Non-existent	No preferred orientation.

(after Brewer 1964)

TABLE 4.14. *Strength: rock and indurated materials*

Term	*Unconfined compressive strength* (MN/m^2)	*Field test*
Very weak	0.60–1.25	Easily broken by hand. Penetrated to about 5 mm with knife.
Weak	1.25–5.0	Broken by leaning on sample with hammer. No penetration with knife. Scratched with thumbnail.
Moderately weak	5.0–12.5	Broken in hand by hitting with hammer. Scratched with knife.
Moderately strong	12.5–50	Broken against solid object with hammer.
Strong	50–100	Difficult to break against solid object with hammer.
Very strong	100–200	Requires many blows of hammer to fracture sample.
Extremely strong	>200	Sample can only be chipped with hammer.

(after BS 5930 1981; ISRM 1981)

TABLE 4.18. *Related particle distribution*

Description	Definition
Porphyritic	The matrix occurs as a dense groundmass in which grains are set after the manner of a phenocryst in a porphyritic rock.
Agglomeritic	The matrix occurs as loose or incomplete fillings in the spaces between grains.
Intertextic	The grains are linked by intergranular braces or are imbedded in a porous groundmass.
Granular	There is no groundmass.

(after Brewer 1964)

TABLE 4.20. *Particle shape*

A. Angularity	A1	Angular
	A2	Subangular
	A3	Subrounded
	A4	Rounded
B. Form	B1	Equidimensional
	B2	Flat
	B3	Elongated
	B4	Flat and elongated
	B5	Irregular
C. Surface Texture	C1	Rough
	C2	Smooth

(after IAEG classification, Anon 1979)

TABLE 4.19. *Particle size classification*

Class	Size limits (mm)	Term
1	>60	Very coarse grained (cobble/boulder)
2	60–2.0	Coarse grained (gravel)
3	2.0–0.06	Medium grained (sand)
4	0.06–0.006	Fine grained (silt)
5	<0.006	Very fine grained (fine silt/clay)

(after IAEG classification, Anon 1979; BS 5930 1981)

field estimation of bulk density can prove a useful index characteristic; its usefulness may be enhanced by comparison with a remoulded density (Table 4.22).

Examples of soils with very low bulk density (from 0.3 to 0.5 Mg/m^3) are the allophanic soils derived from volcanic ash in high rainfall areas. Lower than normal densities (from 0.6 to 1.0 Mg/m^3) are also a characteristic feature of East African halloysitic clays, soils, which are noted for their high porosities.

4.3.8. Behaviour

Material behaviour should be described with respect to the conditions imposed by the nature of the project. In this regard construction procedures are particularly important.

An outline 'soil' list which should be investigated during the field description process is: soaking; drying; remoulding; sensitivity to disturbance; durability (Table 4.23); plasticity (Table 4.24).

Other relevant tests of importance in characterizing the engineering properties of residual soils include (Chapter 5): swell test; shrinkage test; fabric collapse; plasticity; schmidt hammer test; penetrometer/hand vane; quick absorption; pH measurement; field slake test.

TABLE 4.21. *Grading description for coarse grained soils for use with field sieves*

Major divisions	Typical names	Description	Symbols
Gravels: more than 50% coarse fraction retained on 2 mm sieve	Clean gravels	Well graded gravels/gravel–sand mixtures. Little or no fines.	GW
		Poorly graded gravels/gravel–sand mixtures. Little or no fines.	GP
	Gravels with fines	Silty gravels, gravel–sand–silt mixtures.	GM
		Clayey gravels, gravel–sand–clay mixtures.	GC
Sands: more than 50% coarse fraction smaller than 2 mm sieve.	Clean sands	Well graded sands, gravelly sands. Little or no fines.	SW
	Sands with fines	Poorly graded sands, gravelly sands. Little or no fines.	SP
		Silty sands, sand–silt mixtures.	SM
		Clayey sands, sand–clay mixtures.	SC

Notes: adapted from Unified Soil Classification for field use on suitable tropical soil materials. See Chapter 5 for comments on laboratory determinations of particle size gradings.

TABLE 4.22. *Density*

A. Bulk density

Class	Density Soil	Density Rock	Term
1	<1.00	<1.40	Extremely low
2	1.00–1.40	1.40–1.80	Very low
3	1.40–1.70	1.80–2.20	Low
4	1.70–1.90	2.20–2.55	Moderate
5	1.90–2.20	2.55–2.75	High
6	>2.20	>2.75	Very high

B. Relative density

Class	Relative density (%)	Term
1	<20	Very loose
2	20–33	Loose
3	33–66	Medium dense
4	66–90	Dense
5	90–100	Very dense

(after IAEG classification, Anon 1979)

TABLE 4.23. *Durability*

Jar slake index *Ij*	Field test behaviour
1	Degrades to a pile of flakes or mud
2	Breaks rapidly and/or forms many chips
3	Breaks rapidly and/or forms several fractures
4	Breaks slowly and/or forms few chips
5	Breaks slowly and forms few fractures
6	No change

(after Lutton 1977)

4.3.9. Mineralogy

If possible, a field estimation of material mineralogy should be made with particular note being taken of residual minerals (see Chapter 2). An estimation of the percentage occupance of mica is of importance in the prediction of residual soil engineering classification and behaviour (Vargas 1988).

The ratio of residual primary minerals to secondary minerals may be a significant characteristic for definition purposes (Lumb 1965). This ratio should always be considered in the light of the original nature of the parent rock. The nature of the original rock type, particularly its grain size, will naturally influence the effectiveness of any field estimation. Recently reported work on the fabric and mineralogy of granite (Irfan 1988) suggests the possible use of a feldspar grittiness test (Table 4.26).

The estimation of the occurrence and nature of any secondary minerals in the field may be aided by observation of material behaviour during the simple field tests listed in Section 4.3.8 and Table 4.25 above, e.g. the presence of swelling clay minerals.

4.4. Soil mass characteristics

4.4.1. General

The soil mass, which may contain several material types, must be identified and described in terms compatible with the proposed classification system given in Chapter 3 and relevant geotechnical properties (Table 4.3).

4.4.2. Composition

The material components of the soil mass should be identified and recorded in a systematic fashion, as outlined in Section 4.3. This may involve the construction of sections through the profile for instance. It is possible that although the construction of such a geotechnical profile may involve the inclusion of non-residual materials, the end product should always be the geological profile relevant to the nature and properties of the mass in question.

TABLE 4.24. *Field estimation of plasticity*

Class	Term	Definition
1	Non-plastic	A roll 40 mm long and 6 mm thick cannot be formed.
2	Slightly plastic	A roll 40 mm long and 6 mm thick can be formed and will support its own weight, but one 4 mm thick will not support its own weight.
3	Moderately plastic	A roll 40 mm long and 4 mm thick can be formed and will support its own weight, but one 2 mm thick will not support its own weight.
4	Very plastic	A roll 40 mm long and 2 mm thick can be formed and will support its own weight.

(after Hodgson 1974)

TABLE 4.25. *Calcium carbonate content*

Term	Field test behaviour Audible effects	Visible effects	$CaCO_3$ (%)
Non-calcareous	None	None	<0.5
Very slightly calcareous	Faintly audible	None	0.5–1.0
Slightly calcareous	Moderately to distinctly audible: heard away from ear.	Slight effervescence on grains just visible.	1–5
Calcareous	Easily audible	Moderate effervescence; obvious bubbles up to 3 mm diameter.	5–10
Very calcareous	Easily audible	Strong effervescence; ubiquitous bubbles up to 7 mm diameter; easily seen.	>10

(after Hodgson 1976)

TABLE 4.26. *Degree of decomposition of feldspars by grittiness test*

Degree of decomposition	Grittiness term	Scale	Description
Fresh	Hard	1	Cannot be cut by knife; cannot be grooved with a pin.
Moderately	Gritty	2	Can be cut by knife or grooved with a pin under heavy pressure.
Highly to extremely	Powdery	3	Can be crushed to silt sized fragments by finger pressure.
Completely	Soft	4	Can be moulded very easily with finger pressure.

(after Irfan 1988)

4.4.3. Structure

The description of geological structure should include any naturally occurring boundaries and contemporary or relict discontinuities, e.g. joints, bedding, cleavage, faulting and folding/flexuring.

The importance of relict structure, particularly in slope performance, is well documented (Deere & Patton 1971; Brand 1984). The nature and occurrence of these boundaries or discontinuities should be fully defined using accepted standards (ISRM 1980). This definition should include descriptions of infillings and coatings, which may be weathering differentially with

TABLE 4.27. *Discontinuity spacing*

Class	Spacing (mm)	Term
1	>2000	Very widely spaced
2	2000–600	Widely spaced
3	600–200	Medium spaced
4	200–60	Closely spaced
5	<60	Very closely spaced

(BS 5930 1981)

TABLE 4.28. *Contact definition*

A. Boundary distinctness

Class	Boundary Zone Thickness (mm)	Term
1	<5	Sharp
2	5–25	Abrupt
3	25–60	Clear
4	60–130	Gradual
5	>60	Diffuse

B. Boundary form

Class	Description	Term
1	The boundary form is a plane with a few or no irregularities and usually occurs at the same depth across the exposure face.	Smooth
2	The boundary surface has broad shallow relatively regular pockets.	Wavy
3	The boundary surface has pockets which are deeper than they are wide.	Irregular
4	At least one of the horizons is discontinuous and the boundary is interrupted.	Broken

(after Hodgson 1976; Fitzpatrick 1983)

respect to the remainder of the soil mass. The nature of boundaries between materials being described should also be recorded (Tables 4.27 and 4.28).

A description of the mass structure should also include a definition of the spatial relationship of material types forming the soil mass.

4.4.4. Behaviour

As with material behaviour, the soil mass behaviour should also be recorded with respect to the effect of conditions imposed during construction. Field tests may include those undertaken as part of a later ground investigation programme, and could include dynamic penetration tests, the vane shear test, the cone penetration test, pressuremeter/dilatometer tests, in situ CBR tests, plate bearing tests and in situ permeability tests.

Because of the problems of accurately sampling and testing tropical residual soils, it is essential that every effort be made to record in situ behaviour.

4.4.5. Nomenclature

On the basis of the field evidence the residual soil mass should be identified in line with the proposed tropical residual soil classifications given in Chapter 3. The field identification described in this Chapter will form the first judgment as to mass type and performance, which may be refined in the light of subsequent laboratory information.

4.5. Data collection

4.5.1. Procedure

The collection of information for the description of tropical residual soils may utilise the whole range of

TABLE 4.29. *Site investigation procedures*

Procedure	Activity description and comment
A. Desk studies	
Data search	Collation of available maps, references, reports, records. Background information, on geological history, climate, etc. can be collected at this stage.
Remote sensing	May involve techniques ranging from aerial photography to satellite imagery interpretation. Can be used for terrain evaluation and the preliminary organization of projects into convenient sites or soil masses.
B. Field activities	
General mapping	Both geological and geomorphological mapping and may include the recovery of hydrological, vegetational and climatic data. May be used further to define project organization with respect to 'sites', 'masses' and 'materials'.
Boreholes	May be sunk by a number of percussion or rotary methods. The techniques employed should be chosen to take into account the type and condition of material involved. Special precautions and care should be taken in attempting to recover undisturbed samples in sensitive soils or those whose fabric is of geotechnical significance. In some locations options may be restricted by economic or access constraints.
Tests pits	May be either hand or machine dug. Particularly cost effective in the examination and logging of material fabric and the delineation of mass structure. Caution should be exercised in geotechnical interpretation of duricrust masses by test pitting alone where weaker material may underlie stronger. Very useful for obtaining bulk undisturbed samples in sensitive materials.
Augering	Can range from hand augering to machine driven hollow stem augering with undisturbed sampling and in situ testing.
Probing	Relatively inexpensive procedure that can be effective in delineating boundaries to soft or weak materials and in the recording of general in situ material condition. Specific procedures that are currently employed include the Mackintosh probe, the JKR probe and the dynamic cone probe. This may be of limited use in duricrust environments.
Material logging	The systematic recording of material characteristics including the use of in situ behavioural testing. All samples and exposures should be logged using these guidelines.
In situ testing	Includes the range of currently utilized ground investigation in situ techniques, such as Standard Penetration Testing, Dutch Cone Penetration Testing, Pressure Meter Testing, Plate Load Testing, CBR Testing and In Situ Density Testing.
Geophysics	Seismic refraction the most generally used procedure. Best utilized to interpolate or extrapolate in situ conditions in conjunction with boreholes. Caution required in environments where stronger material may overlay weaker. Increased use being made of cross hole seismic work to correlate with geotechnical parameters. The logging of boreholes by means of a suite of geophysical procedures is now a well established ground investigation procedure of particular use in the residual environment. Other geophysical procedures utilized are Resistivity, Gravity and Magnetic.

current site investigation procedures. Although this chapter is primarily concerned with field description, it is relevant to incorporate the various desk activities necessary for most field-based projects.

A full description of site investigation procedures may be obtained from a number of established source references (BS5930; Clayton *et al.* 1982; Dumbleton & West 1974; Weltman & Head 1983). Table 4.29 summarizes briefly the main activities in the context of tropical residual soils.

The establishment of the general site characteristics should be the first step in the process of identification and geotechnical assessment. Table A1 (Appendix) is typical of a form that might be used to collate site characteristics. Used in conjunction with Table 3.3, a completed form such as this may be valuable for preliminary identifications by highlighting the unlikely environments.

Once a likely tropical residual soil grouping has been established a more detailed examination may be undertaken, emphasizing the criteria from Tables 4.2 and 4.3 most relevant to the geotechnical characterization of the soils in question.

4.5.2. Desk studies

Initial desk studies should locate available information and identify potential sources of further data such as previous project work or information held in local Ministries of Works. Typical of such sources are those identified for the Middle East by Eastaff *et al.* (1976). The desk study should also be used to collect preliminary information in respect of site characterization. The early establishment of 'General site characteristics' in conjunction with, for example, a geological or soil map, may provide valuable geotechnical clues to potential engineering performance.

The desk study may be enhanced by the use of remote sensing procedures allied to terrain evaluation principles (Dowling & Williams 1964; Beaumont 1979). By this procedure it may prove possible to identify distinct project land systems together with typical land units or facets.

The effective planning of the ground investigation should be an important part of the desk study and a precursor to field work. The extent and style of ground investigations should take into account the type, stage and economic constraints of the project, together with its geomorphological and geological location (see Table 4.27; Cook & Younger 1986).

4.5.3. Field activities

The objective of the fieldwork programme must be to collect as much relevant information and as many geotechnical behavioural 'clues' as possible, and to relate the information to the proposed classification in Chapter 3. There will generally be an emphasis on the in situ soil profile and its vertical and horizontal variability. In this regard the use of annotated photographs and site sketches may prove valuable.

It is recognized (Mitchell & Sitar 1982) that a range of disturbances may be imposed on a residual soil by different civil engineering activities. It is essential, therefore, that the extent of remoulding or disturbance that occurs in sampling or testing the site materials should be compatible with the likely disturbance due to any proposed engineering activity.

Engineering works are designed to take into account ground conditions and changes in load. As regards ground conditions, the geotechnical engineer must be aware of the extremes that can occur within the design life of the project as this can have a direct bearing on the factor of safety. Work on field description and identification should aim to provide this information. In situ testing is clearly very important with residual soils.

The practical implementation of the field description processes may involve the use of already established techniques of exposure mapping or core logging. The logging of residual soils should follow the guidelines as set out above for soil material and mass descriptions, with the identification of relict structure being an important consideration for many materials. Established core-logging indices such as total core recovery and RQD may be used in the residual soil environment affected by drilling procedures and require careful interpretation. The interpretation and interpolation of core logs in some residual soil environments must be undertaken with extreme caution, for example in establishing the presence or absence of corestones. It is important to recognize that residual soil, as defined in this Report, can exist beneath 'apparent' rock occurrences (see Chapter 2).

5. Testing and sampling of tropical residual soils

5.1. Introduction

As a result of the processes by which they were formed (Chapter 2), tropical residual soils do not usually behave in the same way as unconsolidated sediments. Test procedures commonly used for these sediments and for temperate soils derived from them (e.g. those defined in British and ASTM standards) are not necessarily applicable to tropical residual soils without some modification or change in emphasis. If conventional tests are used on these soils, the usual relationships and correlations might be difficult to establish; other empirical relationships may need to be based on local experience.

The preparation of soil samples for testing demands special care and some accepted practices may not be suitable. This applies both to the preparation of disturbed samples for classification and compaction testing and to the handling of undisturbed samples for shear strength, compressibility and permeability tests.

Conventional index tests on tropical residual soils, although satisfactory for mineralogical classification purposes, should be used with caution when correlating with engineering behaviour. The void ratio of these soils varies considerably and strongly influences their engineering properties. The void ratio may be used as an index in conjunction with easily obtained reference values for these soils.

This chapter presents general guidelines for the preparation and testing of tropical residual soils. Detailed procedures should be assessed by trial for each type of soil.

5.2. Tests for classification of soils

5.2.1. Preparation of disturbed samples

Drying. Even partial drying at moderate temperatures may change the structure and physical behaviour of tropical residual soils. Some of these changes are chemical and are not reversed when the soil is re-mixed with water. They are reflected in changes, sometimes drastic, in the index properties derived from plasticity, shrinkage and particle size tests, or in particle density. Engineering properties such as compaction characteristics, compressibility and shear strength can also be affected (Frost 1976).

Changes in properties can be caused by:

(a) alteration of the clay minerals on partial dehydration (e.g. loss of intra-particle water);

(b) aggregation of fine particles to form larger particles which remain bonded together even on re-wetting.

Clay soils often become more silt- or sand-like, with a lower plasticity; although in some instances the opposite can occur. Oven-drying from 105 to 110°C frequently has a substantial effect on soil properties but drying at a lower temperature (e.g. 50°C), and even partial air-drying at ambient laboratory temperature can also produce significant changes.

Some reported examples of the effects of drying on plasticity and particle size properties compared with tests carried out on natural undried soil are summarized in Table 5.1. Some of the effects are also illustrated graphically on a plasticity chart (Fig. 5.1). Some reported examples of the types of soil that are likely to be susceptible to the effects of drying are listed in Table 5.2.

As a general rule it should be assumed that all tropical residual soils will be affected in some way by drying. Classification tests should therefore be applied to natural soil with as little drying as possible, at least until it can be established from comparative tests that drying has no significant effect on the test results. The method of preparation should always be reported. Suggested preparation procedures are given in subsequent sections of this chapter.

Disaggregation. Disaggregation of tropical residual soil should be done with care and with regard for what is meant by 'individual particles'. The aim should be to separate individual particles without crushing or splitting. For soils in which particles are held together by cement the extent of disaggregation may be limited to that achievable by finger pressure. In some soils it might be preferable to soak in water overnight (with a dispersant if appropriate) and to apply no additional mechanical force.

Sub-dividing. After disaggregation it is essential to ensure that samples are sub-divided by accepted riffling or quartering procedures so that representative samples are obtained for testing.

5.2.2. Moisture content

The conventional definition of soil moisture content is based on the loss of weight when the soil is dried to constant mass at a temperature between 105 and 110°C. In many tropical soils, in addition to 'free' water some exists as water of crystallization within the structure of minerals, and this may be partly removed at that temperature. To identify this type of soil

TABLE 5.1. *Some examples of the effect of drying on index properties*

Soil location and type	Atterberg limits natural $W_L:W_P$	air dried $W_L:W_P$	oven dried $W_L:W_P$	% finer than 2 μm natural	air dry	oven dry
Costa Rica:						
Laterite	81:29		56:19			
Andosol	92:67		66:47			
Dominica:						
Allophane	101:69	56:43				
Latosolic	93:56	71:43				
Smectoid	68:25	47:21				
Hawaii:						
Humic latosol	164:162	93:89		9	0.6	
Hydrol latosol	206:192	61:NP		30	5	
Java:						
Andosol	184:146		80:74			
Kenya:						
Red clay, Sasumua	101:70	77:61	65:47	79		47
Malaysia:						
Weathered shale	56:24	48:24	47:23	25	36	34
Weathered granite	77:42	71:42	68:37	20	17	18
Weathered basalt	115:50	91:49	69:49	80	82	63
New Guinea:						
Andosol	145:75		NP			
Vanuatu:						
Volcanic ash, Pentecost	261:184	192:121	NP	92	57	6

NP indicates non-plastic.

comparative tests should be carried out on duplicate samples taking the measurement of moisture content by drying to constant mass at between 105 and 110°C and a temperature not exceeding 50°C. A significant difference indicates the presence of 'structural' water which is not part of the free water in the usual engineering sense.

For soils on which this difference is confirmed by a number of tests all determinations of moisture content, including those related to other tests, should be made at the lower temperature. Alternatively it may be possible to apply corrections to conventional measurements by allowing for the amount of 'structural' water present, determined as above.

When relating moisture content to liquid and plastic limits, the measured moisture content should be corrected to reflect the soil fraction passing the 425 μm sieve. This fraction can be determined by washing the dried material remaining from the moisture content test on a 425 μm sieve, drying and weighing the fraction >425 μm, and calculating the percentage passing this sieve by difference.

5.2.3. Plasticity tests

If no particles are retained on a 425 μm sieve, water can be added directly to the natural soil, which is then mixed and worked as necessary for the liquid limit and plastic limit tests. The amount of manipulation to which the soil is subjected determines the extent to which the soil structure is broken down. Plasticity tests are done on fully remoulded soil and in some soils a lengthy period of working may be needed to achieve this. The sensitivity of the soil to working and mixing should be verified by using a range of mixing times prior to testing, such as 5, 10, 30 and 45 minutes. The shortest mixing time to ensure homogeneity and full remoulding can then be assessed.

If the soil includes particles >425 μm which cannot be picked out by hand, it should be broken down by soaking in distilled water, not by drying and grinding. The soil is immersed in distilled water to form a slurry which is washed through a 425 μm sieve until the water runs clear. The material passing the sieve is collected and allowed to partially air-dry until it forms a paste of a suitable consistency for mixing prior to testing in the usual way. The coarse particles retained on the sieve are dried and weighed. If the wet mass and moisture content of the original sample have been determined, the percentage by dry mass passing the 425 μm sieve may then be calculated.

For soils containing particles up to fine gravel size the use of a large-scale cone penetration liquid limit

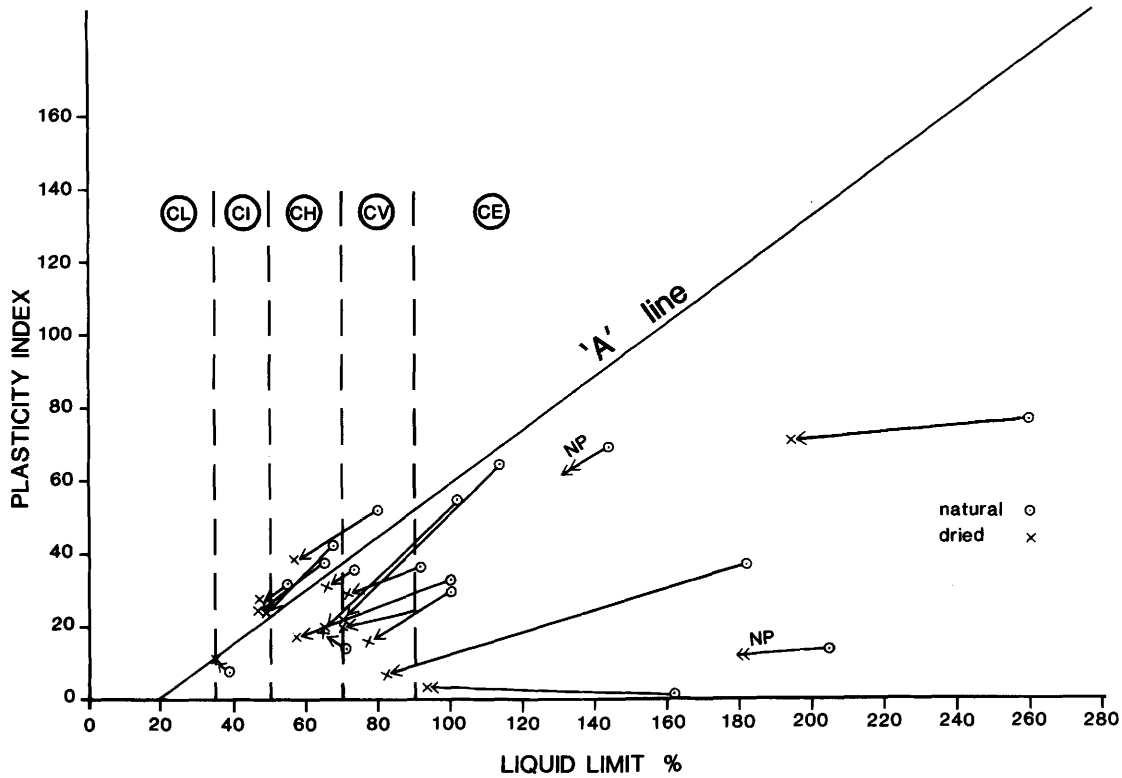


FIG. 5.1. Effect of drying on plasticity for some examples of tropical residual soils.

test has been suggested by Vaughan, Maccarini & Mokhtar (1988). This eliminates the need for removing particles >425 μm, and seems worthy of further investigation.

A one-point liquid limit test should not be used until a suitable empirical relationship has been established locally for each soil type. Data such as those given in BS 1377: 1975 (Clause 2.2.3.5) and Head (Vol. 1, Table 2.6) should not be assumed to be applicable without verification.

Liquid and plastic limits are useful indices for the identification and classification of soils but the conventional categories defined by the 'A' line may need some modification. The use of the liquidity index for correlation with other soil parameters is not recommended and may be misleading.

Classification by means of the plasticity chart can sometimes be enhanced by incorporating a plot of 'activity' (PI/clay fraction), as shown in Fig. 5.2. For this purpose the clay fraction should be expressed as a percentage of the material <425 μm. However, in montmorillonitic soils plasticity may not be related to clay fraction or to specific surface area, although there is a good correlation between liquid limit and the amount of exchangeable sodium (Sridharan, Rao and Murthy 1986).

5.2.4. Shrinkage tests

Some tropical residual soils shrink considerably on drying or expand on wetting. The shrinkage limit test indicates the moisture content below which no further shrinkage takes place and provides some quantitative data for estimating the amount of shrinkage. If shrinkage limit is to be related to the plasticity tests the proportion of soil passing a 425 μm sieve should be used.

The bar-linear shrinkage test provides another indicator of the shrinkage capability, but the relationship between linear shrinkage and plasticity index given in BS 1377 may not be applicable and local correlations for each soil type should be established.

It is important to differentiate soils that shrink irreversibly on drying (or partial drying) and do not expand again when re-wetted, from soils in which the process is reversible (see Section 5.5).

5.2.5. Particle size distribution

Preparation of soil. Drying the soil should be avoided. The initial soil sample is weighed and a duplicate sample is taken for moisture content

TABLE 5.2. *Some tropical residual soils affected by drying*

Location	Soil type	Reference
Brazil		Sandroni (1985b)
Costa Rica	Andosols	Morin & Todor (1975)
Dominica	Allophanes and Latosols	Rouse, Reading & Walsh (1986)
Ghana		Gidigasu (1972)
Guatamala	Andosols	Morin & Todor (1975)
Hawaii	Volcanic ash	Tuncer, Lohnes & Demirel (1978) Lum (1982)
Hong Kong		Brand & Phillipson (1984)
Java	Andosols	Morin (1982)
Keyna	Red clays	Terzaghi (1958) Newill (1961)
Malaysia	Weathered granite Weathered basalt Weathered shale	Fookes, Wilson & Head (pers. comm)
New Guinea	Andosols and Latosols	Morin (1982)
Nicaragua	Latosols	Morin & Todor (1975)
Panama		Morin & Todor (1975)
Puerto Rico	Laterites, Oxisols and Ultisols	Lohnes & Demirel (1973)
Thailand		Moh & Mazhar (1969)

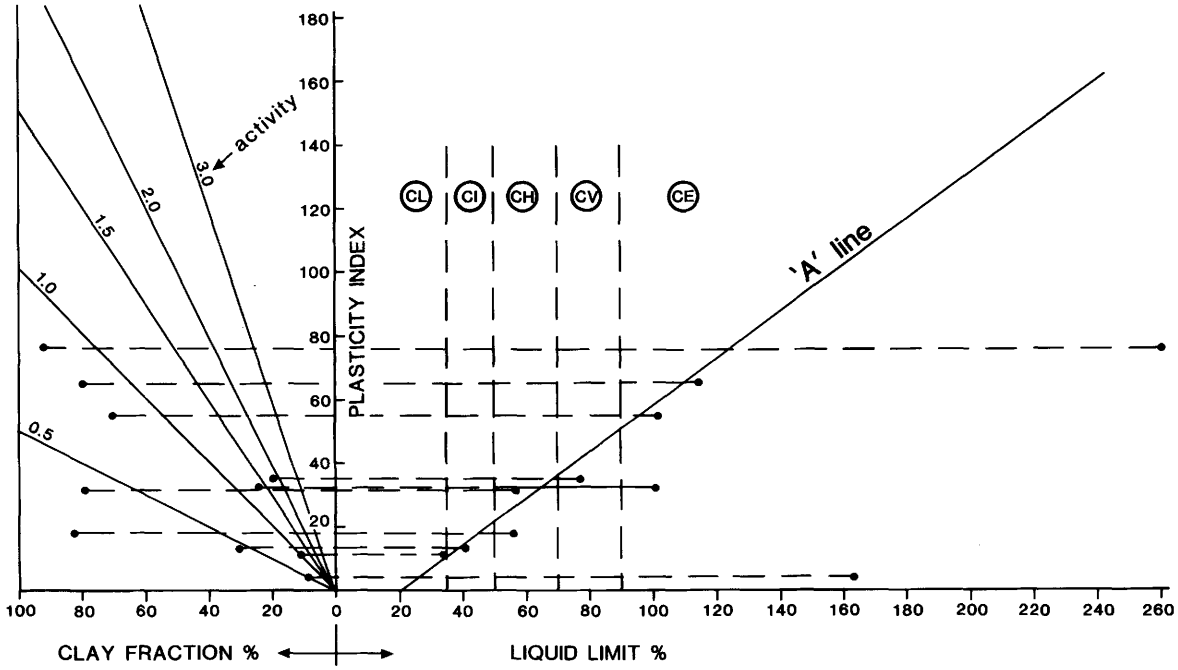


FIG. 5.2. Examples of classification by plasticity and clay fraction.

determination so that the initial dry mass can be calculated. The sample is then immersed in a dispersant solution such as dilute alkaline sodium hexametaphosphate solution for wet sieving. After washing the material retained on the 63 μm sieve can be oven-dried for dry sieving.

Sieving. The detailed procedures to be followed for particle size tests should be judged carefully in the light of experience. Care is necessary at every stage, especially to avoid breakdown of individual particles.

The structure of some soils is such that an appreciable proportion of the clay fraction is contained in the interstices of larger particles. After separating the coarser particles (i.e. those retained on a 20 mm sieve) by wet sieving and instead of drying and weighing them immediately they should be washed in a dispersant solution (sodium hexametaphosphate). When the material is completely disaggregated it is washed on the usual range of sieves and the material passing the 63 μm sieve added to that collected from the initial wet sieving.

Chemical pre-treatment. Chemical pre-treatment should be avoided wherever possible. Treatment with hydrogen peroxide is necessary only when organic matter is present. Treatment with hydrochloric acid is required when it is considered necessary to eliminate carbonates or sesquioxides. The amount of sesquioxides can be determined from chemical analysis of the filtrate from hydrochloric acid treatment. If the proportion of 'free' iron oxide is to be determined alternate treatment with sodium hydrosulphite solution and very dilute hydrochloric acid followed by centifuging, is appropriate.

Sedimentation. Proper dispersion of fine particles is necessary before carrying out a sedimentation test. Alkaline sodium hexametaphosphate has been found suitable for a wide range of soils including many residual soils, but in some instances a stronger concentration of dispersant (e.g. twice the usual concentration) may be required. Occasionally an alternative dispersant, such as trisodium phosphate, may be more effective. Comparative trial tests should be undertaken to establish the most appropriate procedure in each case. The dispersant solution should be freshly made before use.

The effect of drying on the measured clay fraction of some typical residual soils is shown in Table 5.1. The clay fraction is usually defined as the proportion by mass of particles finer than 2 μm. However layer silicate minerals often exceed 2 μm, and a 'clay fraction' based on mineralogy may be more appropriate for correlation with engineering properties. The shape of clay particles may also be significant.

The use of a dispersant may affect the structure of some soils and the test results will not then relate to their in situ characteristics. Test data and the nature of the soil should be carefully assessed to avoid erroneous classification.

5.2.6. Particle density

In residual soils the particle density (also referred to as the specific gravity) may be unusually low or unusually high. If it is not measured and an incorrect assumption is made it could lead to errors in the determination of clay fraction, void ratio and porosity.

The soil should normally be tested at its natural moisture content. After the test the material used can be oven-dried between 105 and 110°C to determine its dry mass for use in the equation for calculating particle density. The gas-jar method (Test 6(A) of BS 1377: 1975) should be used where gravel-size particles are present so that the whole sample is properly represented.

Particle density is required for determining the soil porosity or voids ratio, which can be related to fabric structure. With some clay minerals drying can result in loss of intra-particle water, resulting in a decrease in the measured particle density. This effect can be used as an index property, for instance to distinguish between a soil containing hydrated halloysite and one containing metahalloysite (Newill 1961). This behaviour could have a significant effect on compaction control criteria and must be taken into consideration.

5.2.7. Aggregate strength assessment

Hard materials such as duricrusts are potential sources of aggregates. Their strength for this purpose can be ascertained from aggregate impact value (AIV) and aggregate crushing value (ACV) tests, which are outlined in Collis & Fox (1985). A modified test (AIVM), which may also be done on soaked samples, may be necessary to show up weak material not identified by dry tests alone and to overcome limitations imposed on particle breakdown by the presence of already broken material (Hosking & Tubey 1969; Ramsay, Dhir & Spence 1977)

5.2.8. In situ density

Measurement of the in situ density is essential for assessment of the structural stability of a residual soil and is also necessary for the determination of void ratio (see Section 5.2.9 below). When good-quality undisturbed samples are taken for strength or compressibility tests the density of trimmed specimens is usually obtained as part of the routine procedure. Alternatively the density can be measured in situ, for example by using the sand replacement method (BS 1377, 1975, Test 15(A) or 15(B)). Where coarse particles are present and it is possible to take undisturbed block samples of suitable size, the immersion in water method (BS 1377, 1975, Test 15(E)) avoids the necessity for trimming to a regular shape.

5.2.9. Classification by voids ratio

Vaughan, Maccarini and Mokhtar (1988) have proposed a method of classification applicable to residual soils using void ratios. The reference points chosen for indexing are the voids ratios at the liquid limit (e_L) and at the optimum moisture content (e_{opt}), which gives the maximum dry density when compacted with the 2.5 kg rammer in accordance with Test 11 of BS 1377: 1975.

The 'relative void ratio', e_R is defined by the equation:

$$e_R = \frac{e - e_{opt}}{e_L - e_{opt}}.$$

The equation is comparable with the liquidity index used for the conventional indexing of sediments soils. Using this approach engineering properties are related to e_R rather than just the in situ voids ratio e. Four examples illustrating how soil compressibility varies with the relationship between e, e_R, and e_{opt} are shown in Fig. 5.3.

The proposed limiting void ratios are easy to determine. The value of e_L can be calculated from the liquid limit (w_L) if the mean particle density (ρ_s) is known or can be assumed, using the equation

$$e_L = \frac{w_L \times \rho_s}{100}.$$

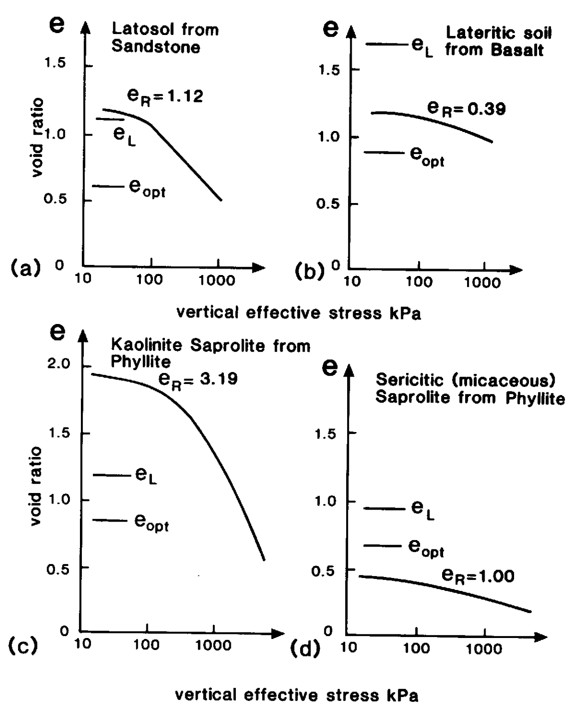


FIG. 5.3. Examples of void ratio used as an index (after Vaughan *et al.* 1988).

The value of e_{opt} is related to the maximum dry density (ρ_{DM}) obtained from the 2.5 kg rammer compaction test by using the equation

$$e_{opt} = \frac{\rho_s}{\rho_{DM}} - 1.$$

Swelling and collapse characteristics are related to changes in voids ratio. In deriving these relationships, it must be appreciated that ρ_{DM}, e_{opt} and w_L can all be influenced by the method of soil preparation.

5.2.10. Soil suction

The relationship between soil suction (pF value) and moisture content in tropical residual soils with unstable structure differs from that of unconsolidated sediments and temperate soils. A typical wetting and drying cycle for unconsolidated sediments or temperate soils is represented by the hysteresis loop ABCDA in Fig. 5.4. During the drying stage of a tropical residual soil a sudden increase in loss of moisture may occur when the soil suction reaches a 'break-through' point, due to collapse of the structure. This is indicated in Fig. 5.4 by the curve CEF. If the moisture content at the break-through point lies between the PL and LL of the soil, the soil when at the plastic limit is not in the same state as the natural soil. If the break-through occurs below the PL then there is little or no change in state between the plastic limit and the natural condition. However, if the soil is wetted again from a dry condition, the irreversible change in structure of some soils will result in the emergence of a new hysteresis pattern of drying and wetting cycles.

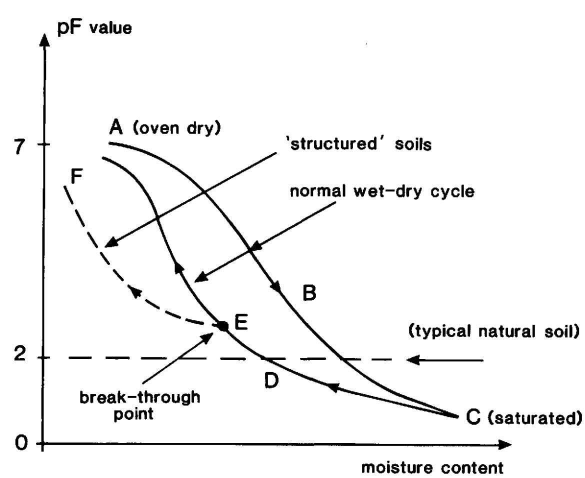


FIG. 5.4. Representation of relationships between soil suction (pF) and moisture content.

5.3. Compaction related tests

5.3.1. Sample preparation

With tropical residual soils it should be assumed that the coarser particles are susceptible to crushing and therefore a separate sub-sample of soil is needed for compaction at each moisture content to avoid successive degradation. This also applies to the breakdown of the <425 μm fraction, referred to in Section 5.2.3.

For soils that are sensitive to drying, problems can arise with compaction control in the field. The soil should not be dried before testing in the laboratory. When it is necessary to compact specimens at moisture contents lower than the natural moisture content specimens should be partially dried at room temperature until each desired moisture content is reached. Excessive drying, requiring re-wetting, should be avoided. For a given degree of compaction drying has generally been found to increase the maximum dry density and to reduce the optimum moisture content. Data obtained from tests on dried soil are not applicable to the field behaviour and could result in inappropriate criteria being applied to field conditions.

Soils from arid regions should be wetted in batches as required and stored for at least forty eight hours before use in compaction tests. Longer maturing periods may be more appropriate to simulate on-site wetting procedures. A series of comparative tests using different maturing periods may be desirable.

5.3.2. Compaction

Residual soils are generally modified by compaction. The degree of compaction used in the laboratory should relate to that likely to be used in the field. Compaction equivalent to the BS '2.5 kg rammer method' is usually adequate for these soils, greater compaction often leading to excessive breakdown of particles.

If the in situ density of a soil is measured, compaction of the same soil at its natural moisture content using the 2.5 kg rammer procedure provides a reference state in terms of void ratio to which the in situ void ratio can be related (as outlined in Section 5.2.9).

Differences between the densities obtained in laboratory tests and those measured after compaction in the field may be greater for tropical residual soils than for sediments or temperate soils. The energy applied by compaction in the field may not be enough to produce complete structural breakdown of the soil, which is more readily obtained in a laboratory test. Subsequent applied stresses, if high enough (e.g. in high embankments), can cause additional structural collapse. The use of high energy compaction may then be desirable.

For hard materials used in pavement construction heavy compaction equivalent to the BS 4.5 kg rammer method is usually appropriate. It is then important to ascertain the extent of particle breakdown due to compaction. A 'fully disaggregated' state is obtained by recompacting the same material several times until no further significant breakdown occurs.

5.3.3. California Bearing Ratio (CBR)

Undisturbed samples for laboratory CBR tests should be taken with great care to avoid disturbance of the soil structure (see Section 5.10.5).

In areas of high rainfall the CBR value in the soaked condition is critical and the amount of expansion during soaking should be measured. In some soils, very low soaked CBR values have been obtained which are independent of the water content at which the samples are compacted. Account should be taken of seasonal variations when selecting design CBR values, which should be based on the wettest condition.

CBR values derived from tests on laboratory-compacted samples depend to a great extent on density, which for construction control purposes is usually related to maximum dry density at optimum moisture content. Any variation in these reference values due to drying the soil before testing could have a significant effect on the results.

CBR tests may also be carried out in situ on a subgrade, which could be either of natural soil or of soil which has been compacted in a specified manner. In many ways the dynamic cone penetrometer (DCP) is a preferable and less expensive alterntive to in situ CBR tests.

5.3.4. Moisture condition value (MCV)

The MCV test should be applied to tropical residual soils with caution. The conventional methods of interpreting the calibration curve and the blows/penetration curve may not be appropriate for 'structured' soils. As yet there is little published information on this procedure and each soil should be carefully investigated.

5.4. Strength and sensitivity

5.4.1. Characteristics of tropical residual soils

Some of the characteristics of residual soils which have a significant influence on their shear strength are as follows.

(1) The presence of bonding between particles, giving a component of strength and stiffness which may be easily destroyed, i.e. a brittleness effect.

(2) Widely variable void ratio which is unrelated to stress history.

(3) Partial saturation, possibly to considerable depth, which can be responsible for disturbance during sampling as well as the behaviour observed in a test.

These and other characteristics are discussed in Chapter 6. Suggested testing procedures taking these factors into account are outlined below.

5.4.2. Quality of samples

The measurement of shear strength of tropical soils requires samples of high quality. Hand-cut block samples or core samples of large diameter (not less than 75 mm) should normally be used. Test specimens of smaller diameter cannot truly represent the effects of coarse particles or soil fabric features such as joints and fissures.

Sample disturbance can alter the structure of residual soils. Stress relief on exposing the soil to be sampled is itself a cause of disturbance. Great care must be exercised to prevent disturbance when extracting samples from the ground, transporting them to the laboratory, extruding and preparing them for test. Stiff brittle soils especially should be handled carefully to prevent fracturing. Undisturbed samples should receive adequate protection against loss of moisture at all times.

Disturbance of test samples is a major cause of erratic shear strength data. For example, desiccated decomposed mudrock can give very low shear strengths, whereas the partial collapse of structure in a disturbed sample of weathered granite can result in an increased value of ϕ' being measured.

5.4.3. Total stress measurements and sensitivity

Shear strength in terms of total stress and sensitivity to remoulding is particularly relevant to saturated residual soils. Unconfined compression tests or quick-undrained triaxial compression tests at suitably low confining pressures are applicable to these soils. For the reasons given above, test specimens should be large enough to enable the soil fabric to be adequately represented. Specimens of a height:diameter ratio of less than 2:1 down to about 1:1 may be satisfactory if lubricated end platens are used (Head 1982). For fine-grained soils containing no coarse particles conventional 38 mm diameter specimens are adequate.

The laboratory vane apparatus is useful for determining the remoulded shear strength (which gives 'lower bound' value of strength) from which the sensitivity of fine-grained soils is derived. For fine-grained soils that are too soft to allow satisfactory laboratory vane test can be carried out in the sample container, first on the undisturbed soil and then immediately after remoulding at the same moisture content. The 'undisturbed' strength of these soils is realistic only for samples of high quality, such as are obtained by piston sampling.

5.4.4. Effective stress measurements in partially saturated soils

Many in situ tropical residual soils are in a partially saturated condition in which total stress measurements are not applicable. When only the determination of the effective shear strength parameters c', and ϕ' is required saturation of the test specimens by the application of back pressure is not necessary, provided that the pore water pressure is always greater than atmospheric pressure. However when the measurement of volume change using the flow of water into or out of the specimen is required, the usual procedures for applying full saturation should be followed.

For soils containing particles larger than about 10 mm and when only the parameters c', and ϕ' are required, these values can be determined from drained shear tests carried out in a large shearbox (i.e. about 300 mm square). Where the nature of the soil is such that larger samples would be necessary, in situ direct shear tests would be more convenient.

Saturation of triaxial specimens often requires back pressures higher than the pore pressures prevailing in most field situations, but this is generally acceptable in preference to the erratic results which may be obtained due to incomplete saturation. Increasing the degree of saturation appears to reduce the value of c' in many residual soils, due to an associated decrease in soil suction. The increase in moisture content due to saturation can cause changes in other components of inter-particle forces leading to a reduction of shear strength. However some investigators have found that the value of ϕ' is not significantly altered by saturation (Bressani & Vaughan 1989).

In some instances specimens of partially saturated residual soils have been tested at both natural moisture content and after soaking. Comparison of the strength envelopes obtained allows the influence of pore water suction on the effective stress to be determined. Other methods for examining the effect of pore water suction on strength are discussed by Fredlund & Rohardjo (1985).

The stiffness of the soil fabric can be affected by saturation and this becomes evident in changes in the stress–strain relationships. The degree of weathering of the soil can have a similar influence.

The effect of saturation over a range of moisture conditions for lateritic materials containing clay was investigated by Toll *et al.* (1988). They demonstrated the soil was dried to a moisture content lower than the optimum moisture content used for compaction.

5.4.5. Bonding between particles

The shear strength of a bonded soil may be underestimated if during a test the combination of shear stress and average effective stress causes yield of the bonded structure. This can be minimized by limiting the effective confining pressure to a suitably low value, possibly about 50 kPa, but it may be better to consider the combined stresses in terms of the stress path to be followed for the test.

The selection of a suitable stress path avoids premature loss of bonding between particles. In a study of residual soils from Hong Kong (Geotechnical Control Office Hong Kong 1982), conventional effective stress triaxial compression tests required large strains (up to 10 percent) before failure occurred. The effect of shearing to these large strains was to break the inter-particle bond. However when failure was induced by increasing the pore pressure at a lower constant applied shear stress, the strains at failure were appreciably smaller and higher drained strengths were measured. The two procedures are compared in the stress path diagram shown in Fig. 5.5 and illustrate the necessity of keeping a laboratory test within the limits of yield likely to occur in situ.

5.4.6. Void ratio and grain structure

In soils that have a sensitive grain structure associated with a high void ratio, care should be taken to avoid the application of an excessive rate of loading. The conventional rate of strain applied for a compression test, derived from drainage criteria, can give rise to a very high rate of stress increase at low strains. To avoid this some form of stress control should be substituted for the usual strain control.

Multistage triaxial compression tests should be used with caution for tropical residual soils, especially those with an unstable structure liable to collapse, brittle soils and soils that show strain-softening characteristics.

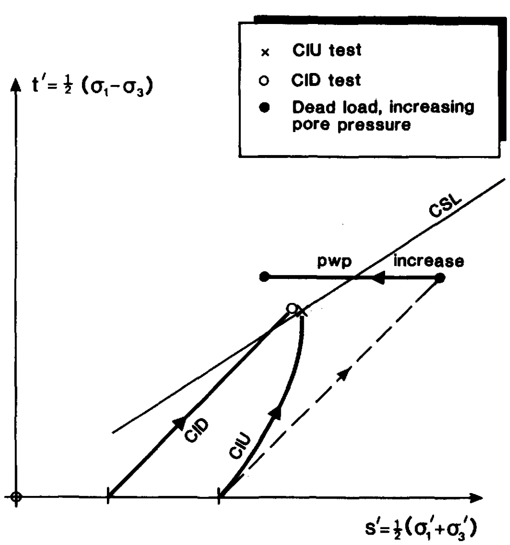


FIG. 5.5. Failure of residual soils with bonding, following different stress paths.

5.4.7. Residual strength

The residual strength can be a useful indicator of clay mineralogy. For fine-grained soils multi-reversal shearbox tests are commonly used for determination of the residual shear strength. Specimens are normally saturated by percolation before testing. For residual soils containing coarse material, e.g. decomposed granites, the use of a large shearbox is appropriate.

The shear strength along existing surfaces of a discontinuity can be measured in the shearbox apparatus if undisturbed specimens are carefully taken and set up with the plane of discontinuity in the correct alignment. Alternatively, triaxial compression tests can be made on large diameter specimens suitably inclined to induce failure along a discontinuity.

5.4.8. Correlation with index properties

It may be difficult to relate the shear strength of tropical residual soils to index properties such as Atterberg limits or liquidity index as is normally done for other soils. Attempts to relate liquid limit properties to engineering properties of residual soils generally give a scatter, or possibly a weak trend which may be misleading. In contrast, the structure of the soil is crucial. Since this is dependent on voids ratio, the bulk density and dry density of specimens used for tests should always be measured as a routine procedure. Shear strength can then be correlated with 'relative void ratio', as defined in Section 5.2.9.

5.5. Expansive clays

Expandible clay minerals frequently occur in tropical residual soils. They are generally clays of medium or high plasticity which, when lying above the water table, show a high degree of shrinkage on drying. When wetted they swell, exerting high pressures. Light structures supported in the zone of seasonal changes of moisture content are thus susceptible to damage. The clay mineral commonly associated with volume change is smectite, which can be readily identified (see Section 5.8.2). Most problems occur within about one metre below the surface.

An indication of the likely swelling potential of clays is provided by the Atterberg limits; swelling generally increases with increasing liquid limit and plasticity index. The volumetric shrinkage curve obtained from a shrinkage limit test (Head 1980, Vol. 1, 2.7) provides a more direct assessment but this test may be difficult to carry out properly on some residual soils. Linear shrinkage (BS 1377: 1975, Test 5) is an alternative indicator, especially for lateritic clays, and measurement at intervals during drying provides a field test for obtaining a shrinkage curve.

A plot of plasticity index against clay content provides a means of classifying potential expansiveness (Mori 1982). Another simple procedure is the 'free swell test' (Gibbs & Holtz 1956) referred to by Morin & Todor (1975). Swelling potential can also be assessed from an empirical relationship based on plasticity index, soil suction and applied stress (Brackley 1980).

Swelling characteristics can be investigated qualitatively by laboratory oedometer tests. The swelling pressure or equilibrium stress is the pressure required to just prevent swell when the test specimen is flooded with water (see Fig. 5.6) (Head 1982, 14.6.1). The swelling capability, in terms of an $e/\log p$ curve, can be determined by measuring the swell of the specimen as the applied pressure is reduced in stages below the swelling pressure (curve A in Fig. 5.6). However the values obtained from these tests should be used with caution in view of different boundary conditions prevailing in situ. In the double oedometer test (Jennings & Knight 1957a) one of the specimens is soaked and allowed to swell until it reaches equilibrium with no applied load. It is then consolidated under the usual increments of loading (curve B in Fig. 5.6) and settlements are compared with those obtained from unsoaked tests on an identical specimen.

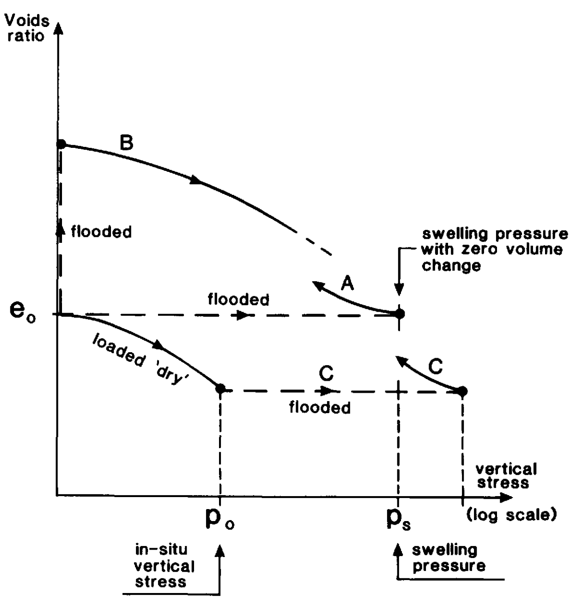


FIG. 5.6. Measurement of swelling characteristics of expansive clays.

A procedure which represents field conditions more closely than those referred to above is to first apply the appropriate in situ vertical stress until equilibrium is reached and then flood with water, maintaining constant volume before allowing swell (curve C in Fig. 5.6). High-quality undisturbed hand-trimmed block samples are essential for these tests. As pore suction is critical it is essential to prevent loss of moisture from samples between the in situ state and the start of the laboratory test. Some examples of residual soils that exhibit swelling characteristics are described by Blight (1982), Gidigasu & Andoh (1980), Horn (1982), Lum (1982), Schreiner (1987) and Williams (1980).

5.6. Collapsing soils

Collapsible soils have an open-textured fabric which can withstand reasonably large stresses when partly saturated, but undergo a decrease in volume due to collapse of the soil structure on wetting, even under low stresses. Partially saturated tropical residual soils are frequently of this type. Collapse settlement usually results from loss or reduction of bonding between soil particles due to the presence of water and often occurs in intensely leached residual soils formed from quartz-rich rocks. Other collapse mechanisms include loss of the stabilizing influence of surface tension in water menisci at particle contacts in partly saturated soil and loss of strength of the particles themselves when wetted.

Collapse characteristics can be investigated in the laboratory by means of a special oedometer consolidation test. The test specimen is first loaded at its natural moisture content, without adding water to the cell, to a pressure typically equal to the anticipated in situ stress. When equilibrium is established, water is added to the cell and a collapsing soil undergoes immediate settlement under the same applied stress. Additional loading can then be applied in the usual manner with the soil saturated. A typical $e/\log p$ curve for a collapsing soil is shown in Fig. 5.7.

In the collapse potential test (Jennings & Knight 1957b) the sample is saturated after loading to 200 kPa. The collapse potential is equal to:

$$\frac{\delta e}{1+e_0} \times 100\%$$

where δe is the change in voids ratio on saturation and e_0 is the initial voids ratio of the sample. Table 5.3 indicates the likelihood of collapse being a problem.

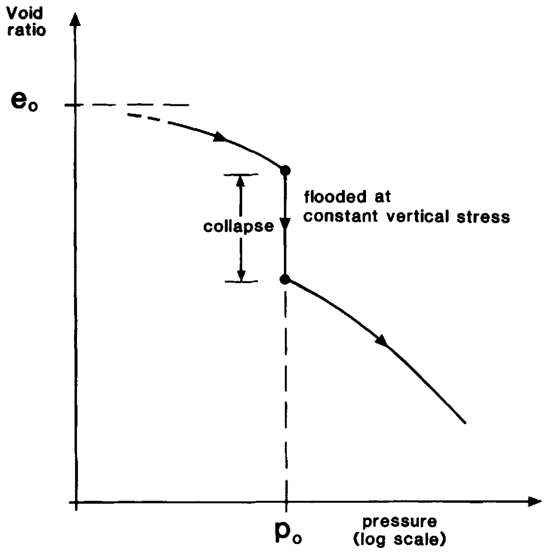


FIG. 5.7. Behaviour of a collapsing soil.

TABLE 5.3. *Guidance for collapse potential*

Collapse potential (%)	Likely severity of problem
up to 1	No problem
1 to 5	Moderate trouble
5 to 10	Trouble
10 to 20	Severe trouble
above 20	Very severe trouble

Swelling and collapse characteristics depend on voids ratio and applied stress. Some soils can exhibit either swelling or collapse under different conditions.

For the study of collapse characteristics undisturbed samples of high quality, hand-trimmed from carefully-taken block samples, are essential. If oedometer tests indicate that a soil collapses on wetting additional tests should be carried out under isotropic stress in the triaxial apparatus to confirm that collapse is an intrinsic property of the soil. However predictions of in situ soil behaviour from laboratory tests alone are not reliable unless supported by in situ tests and by observations of the performance of foundations.

Some examples of residual soil types which exhibit collapse characteristics were reported by Brink & Kantey (1961), Foss (1973), Singh & Al-Layla (1980) and Vargas (1973, 1974).

5.7. Dispersive and erodible soils

5.7.1. Dispersive soils

Dispersive soils, in the engineering sense, are those which are susceptible to internal erosion and piping due to deflocculation in the presence of relatively pure water. Any soil containing a high exchangeable sodium percentage (ESP) is likely to be dispersive a correlation between liquid limit and ESP for montmorillonite soils is referred to in Section 5.2.3. Residual soils with dispersive characteristics include those with clay fractions consisting mainly of smectite, vermiculite, halloysite, non-crystalline allophane or some illites; but rarely of kaolinites. Dispersive soils can occur in both wet and arid regions.

The laboratory tests widely used to indicate whether or not a soil is likely to be dispersive or erodible are the determination of the Emerson Class Number of a soil (Emerson 1967; Standards Association of Australia 1980), the Crumb test (Sherard *et al.* 1976; Head 1982), the SCS double hydrometer test (Sherard, Dunnigan & Decker 1976; Head 1982) and chemical tests on pore water extracted from the clay, to determine total dissolved solids, the ESP value, and the sodium absorption ratio (SAR) (Sherard, Ryker & Decker 1972).

5.7.2. Erodible soils

Pinhole test (*ASTM D 4647-87*). Laboratory tests such as those listed above are useful for providing a general indication of behaviour but are no substitute for careful field observations. Blight (1982) suggested that the Emerson test and the SCS double hydrometer test are the most satisfactory. The weakly-cemented nature of some residual soils can cause difficulties in the preparation of specimens for the pinhole test, in performing the test and in interpreting the results.

These tests should all be carried out on soil at its natural moisture content. Wherever possible the actual groundwater should be used. Drying causes changes to the dispersive characteristics. Tests should be carried out on samples taken at close vertical depth intervals as dispersibility can vary considerably with depth.

5.8. Chemical tests

5.8.1. Routine tests

Some routine chemical tests applicable to tropical residual soils are listed in Table 5.4. Major element analyses of certain tropical soils, especially ferrallitic types (Gidigasu 1976), are widespread in the literature. Many were done for economic purposes, such as evaluating bauxites. Silica-sesquioxide ratios can be determined from major element analyses as follows:

$$K_r = \frac{\%SiO_2/60}{(\%Al_2O_3/102) + (\%Fe_2O_3/160)}.$$

This is commonly used to indicate the extent of

TABLE 5.4. *Routine chemical tests applicable to tropical residual soils*

Property determined	References
Major element content	Pruden & King (1969)
Organic matter content	BS 1377 (1975) Test 8 Kalembasa & Jenkinson (1973) Head (1980) 5.7
Loss on ignition	Head (1980) 5.10
Sulphate content	BS 1377 (1975) Tests 9 and 10 Head (1980) 5.6
Carbonate content	Bascomb (1961) Head (1980) 5.8
Chloride content	Head 1980 5.9
pH value	BS 1377: 1975 Test 11 Schachtschabel (1971)
Cation exchange capacity	Bascomb (1964) Gillman (1979)

weathering and to differentiate soil types. Values of $K_r < 2.0$ are typical of oxide-rich ferrallitic soils, ferrisols and some ferruginous soils whereas fersiallitic and some ferruginous soils have K_r values >2.0; ferrites, ferrallites, allites and most indurated ferrallitic soils have K_r values <1.33. However, much depends upon the composition of the soil parent material and on the concentration of either silica or sesquioxides by processes other than weathering (e.g. accumulation of Fe_2O_3 by podzolization or hydromorphic segregation). Hence the ratio does not correctly classify all tropical soils in the French or any other system given in the Appendix to Chapter 2.

Major element analyses can be used to recast bulk mineralogical composition if the constituents have been identified and their individual chemical compositions are known fairly precisely. For example, quantitative clay mineral composition can be calculated in this manner from semi-quantitative X-ray diffraction results. In addition as mentioned in Section 5.9 major element composition provides the best evidence for mineralogical composition if poorly crystalline or amorphous constituents, which cannot be identified by X-ray diffractometry, are present. With bulk analyses of clay-rich soils, as most of the Al_2O_3 occurs in clay minerals, it is often useful to express the amounts of major elements as ratios to total Al_2O_3 and a fairly accurate impression of the mineralogical composition of a clay fraction is then obtained without its separation.

5.8.2. X-ray fluorescence spectroscopy (XRF)

This simple, rapid method of chemical analysis is often used to determine the major and minor element composition of soil samples. This is satisfactory for most elements with an atomic number >10, but Na, Mg and Al cannot be determined very accurately. The method entails excitation of elements in a homogenized sample of soil (powdered and compressed or fused with sodium borate or lithium tetraborate) so that they emit characteristic radiation. The fluorescent radiation is usually dispersed by diffraction using suitable crystals and the diagnostic fluorescence wavelengths of each element measured by a proportional or scintillation counter (Norrish & Chappel 1967; Jasmund 1979). The concentration of each element is determined by comparing the intensity of its diagnostic wavelength line with the intensities of the sample lines in reference standards of known composition. Carefully selected standards are available from the US Bureau of Standards and British Chemical Standards. One of the problems with compressed powdered specimens is that the fluorescent radiation from the specimen surface is not necessarily representative of the whole. Fusion, perhaps followed by fine grinding of the resulting glass to produce a powder from which a compressed disc can be prepared, is therefore the preferred method of sample preparation.

5.8.3. Cation exchange capacity (CEC)

The total cation exchange capacity (sum of negatively charged sites occurring mainly on alumino-silicate clay minerals and organic matter) is best determined in tropical and other strongly weathered soils by saturation with barium ions, displacement of the barium with magnesium, and then determination of the amount of displaced barium by atomic absorption spectrometry (Gillman 1979) or by titration with standard EDTA solution using Omega Chrome Black VS as an indicator (Bascombe 1964). For strongly calcareous samples two treatments with a barium solution (usually barium chloride) are necessary, the first to precipitate any soluble bicarbonate. Saline soils should be shaken with a 1:1 water:ethanol mixture for one hour, then centrifuged and the supernatant discarded before proceeding to the barium-saturation treatment. The results are expressed as milliequivalents (mEq) per 100 g soil on an oven-dry basis (weight of soil dried at 105°C). Problems associated with CEC determination are discussed in detail by Rhoades (1982).

If the CEC is determined on a separated clay fraction it can provide some evidence of mineralogical composition (Table 5.5). On a total soil basis allowances must be made for the proportions of sand and silt, which usually have little or no exchange capacity, and of organic matter which has a variable capacity.

CEC has two components: (a) a permanent negative charge resulting from isomorphous substitu-

TABLE 5.5. *Typical cation exchange capacities of clay minerals (Grim* 1968)

Mineral	CEC/mEq/100 g
Kaolinite	3–15
Halloysite	5–50
Illite	10–40
Chlorite	10–40
Allophane	25–50
Smectite	60–150
Vermiculite	100–150

tion in clay minerals, and (b) a variable, pH-dependent negative charge attributable to organic matter, broken bonds at the edges of clay particles and the dissociation of accessible hydroxyl groups in clay minerals. The barium saturation should therefore be carried out at a standard pH, either 7.0 by buffering the barium chloride solution with barium hydroxide or 8.1 by buffering with triethanolamine.

5.9. Soil mineralogy and microstructure

For most engineering work it is not usually necessary to take investigations of soil physical properties beyond the determination of Atterberg limits. However in tropical soils the influence of microstructure is important (Collins 1985) and, as in other soil types, the effects of swelling clay minerals and colloidal size constituents can be significant. For these reasons it is often important to resolve microstructure, fabric and mineral composition of soils under test. The most commonly used methods are optical microscopy, scanning electron microscopy, X-ray diffraction and thermal analysis.

5.9.1. Use of optical microscope

Examination of thin sections by use of a polarizing microscope facilitates identification of mineral grains larger than about 10 μm and their relationship to other constituents in two dimensions. Although the optical microscope has little depth of focus, soil profile development can often be inferred from thin sections taken from successive horizons. The various soil microfabric elements seen in thin section are defined by Bullock *et al.* (1985), and include features resulting from mineral weathering, illuviation of clay and other particles, reorientation of particles by shrinking and swelling, hydromorphic segregation of iron and manganese, or the activities of soil animals.

Soft clays or friable soils should be sampled carefully in the field using rectangular tins with sharp edges and removable tops and bases (Kubiena tins). Impregnation with resin which can be hardened subsequently is a necessary pretreatment before cutting, grinding and polishing to the correct thickness (Murphy 1986). Sections approximately 30 μm thick are studied by transmitted light at magnifications of $\times 30$ to $\times 1000$ which allows identification of all except ore minerals by properties such as colour, pleochroism, birefringence, optic sign, optic axial angle and optic orientation (Nesse 1986). Opaque ore minerals are identified in reflected light (Craig & Vaughan 1981).

Point counting may be used to estimate mineral abundancies or porosity. A large number (>300) of grains or voids are identified at grid intersections located by cross-hairs in the microscope eyepiece using a travelling point-count stage attachment. The percentage of each mineral or of pores is calculated from the proportion of points assigned to it; this gives a reliable volumetric percentage provided there is no major anisotropy in the sample (Chayes 1956).

Staining techniques are commonly used to help identify minerals such as carbonates, feldspars and clay minerals in thin section. Individual clay mineral platelets are usually too small to be resolved with an optical microscope, but organic dyes have been used with some success to identify clay mineral aggregates (Taylor 1985), especially smectite (Sameshima & Black 1979). However care must be taken to avoid dye being retained on polished mineral surfaces and in depressions in the surface of the thin section (e.g. at grain boundaries), which would give rise to misleading results.

As thin sections show a limited volume of soil, rare mineral constituents in fine sand (62–250 μm) or coarse silt (10–62 μm) fractions are better identified by microscopic examination of these size fractions separated from dispersed soil samples by sieving and repeated settling in water. The assemblage of sand or silt minerals is often a good indication of the soil parent material, provided allowances are made for possible weathering effects. Both parent material and the effects of weathering can vary through a profile and some technique of multivariate analysis such as principal coordinate analysis (Mardia *et al.* 1979) may be required to distinguish them.

5.9.2. Scanning electron microscopy (SEM)

The considerable depth of focus of the SEM makes this instrument especially valuable in the study of soil microstructure and for confirming the presence of specific minerals (including clay minerals) from their characteristic morphologies. The SEM exploits properties which arise when a beam of electrons strikes a target. The beam is absorbed, reflected or transmitted. SEM normally utilizes an incident beam of electrons in the range of 1 to 50 keV. This is made to raster over a small area of the specimen and is synchronized with a TV monitor to produce an image related to the reflected electrons or the secondary electrons which are back-scattered. Valuable introductions to this technique with sediments are given by Smart & Tovey (1981, 1982) and McHardy & Birnie (1987).

Although most SEM observations exploit the topographic contrasts provided by the back-scattered mode, Table 5.6 lists the information that can be obtained from an SEM operating in appropriate modes. In the investigation of soil microstructure and the morphology of minerals emphasis is directed to the topography of the surface and the contrast arising chiefly from changes in the angle of tilt which the specimen makes with the beam.

Specimens are usually prepared by making a freshly broken surface from which loose fragments can be carefully removed with sellotape. The base of the specimen should be smooth and fixed firmly to the specimen stub with a good conductor such as silver. As resolution is impaired by non-conductive materials, the soil specimen must also be coated with a thin layer (approximately 20 nm) of gold–palladium, carbon or other conducting material. This provides a path to earth for any surface charge induced by the beam. Coating is usually accomplished by evaporation or sputtering in a vacuum chamber.

Observations of microstructure and soil fabric are conveniently made at magnifications of ×200 to ×1000, but to study the morphology of clay minerals a resolution of 5 to 10 nm is required. Based on classical soil fabric models Brewer (1964) and Collins & McGowan (1983) developed a microfabric characterization scheme suitable for engineering purposes. This has been extended by Collins (1985) to include tropical soils. Morphological characteristics of clay minerals are illustrated by Van Olphen & Fripiat (1979).

Most SEM studies of the microstructure of tropical soils have been qualitative in nature, although the level of measurement can be improved by taking stereoscopic pairs of photographs. These can be produced by photographing the image before and after a small change in the angle of tilt. Measurements can then be made using a conventional stereoviewer.

TABLE 5.6. *Types of information obtainable from various SEM modes*

Type of information	Modes
structural and topographic	back-scattering, reflective, absorptive, conductive luminescent
chemical composition	X-ray, Auger electrons, reflective luminescent, absorptive
crystallographic	X-ray (Kossel pattern lines), transmissive, electron channeling pattern
electric and magnetic	back-scattering, reflective, conductive

Transmission electron microscopy (TEM) has also been used to study dispersed clay fractions. It shows the shapes of individual particles, and the crystal structure can often be obtained from electron diffraction patterns.

5.9.3. X-ray diffraction (XRD)

X-ray diffraction is indispensible for identifying the minerals present in tropical soils, and as the equipment is now more readily available the technique should be used as a routine wherever possible. Details of sample preparation, operating conditions and semi-quantitative determination of various minerals are given by Thorez (1976), Klug & Alexander (1974), Dixon & Weed (1977) and Brindley & Brown (1980).

X-ray diffractometers incorporating modern crystal monochromators have considerable advantages for mineralogical analysis of iron-rich tropical soils. If older equipment is used, an iron or cobalt anode X-ray tube is preferable to a copper tube which is likely to induce iron fluorescent radiation. Ultrasonic treatment of tropical soil samples helps disaggregation and decreases the masking of mineral grains by ferruginous coatings. For whole sample analysis the grain size of a representative subsample should be carefully reduced to less than 5 to 10 μm. Powders can then be analysed either as fillings in cavity mounts or as smear mounts on a glass slide. For the latter, the powder is made into a slurry with water, smeared on to the slide and allowed to dry; layer silicate particles are orientated parallel to the slide surface as the slurry dries. With very fine samples rich in poorly crystalline clay, it is useful to separate the clay fraction ($<2\ \mu$m) or even subdivide it (0.6–2.0 μm, 0.2–0.6 μm and $<0.2\ \mu$m) by settling under gravity or centrifuging in aqueous suspension and analyse each fraction separately.

All crystalline materials have unique X-ray diffraction patterns. In practice the diffraction peaks are first identified on the output chart and measured as an angle (2θ), which is twice the glancing angle (θ) of the diffracted X-ray beam. The 2θ values are then converted to lattice spacings (d) in Angstrom units (Å) using the Bragg equation; Parrish & Mack (1963) give conversion tables. Angstrom units are still used in clay mineralogy although they are not approved S.I. units. The relative intensities of all diffraction peaks are also recorded at this stage.

Standard reflection patterns for minerals in terms of d-spacings and relative intensity of peaks are continuously updated by the Joint Committee on Powder Diffraction Standards (JCPDS). The patterns for minerals in the samples analysed can therefore be identified by searching the JCPDS Powder Diffraction Index (1974). In addition, Brindley & Brown (1980) and other texts list the main diagnostic peaks and intensities of minerals likely to occur in soils.

Clay mineral identification presents a number of problems which necessitate additional treatment of the powders. For smectites, ethylene glycol treatment or saturation with certain cations expands the alumino-silicate layers to characteristic *d*-spacings and heating to 375°C collapses the expandable layers to 10 Å. Vermiculites and halloysites also require special treatments for identification, as do mixtures of clay minerals with overlapping reflections (e.g. identifying 7 Å halloysite in the presence of kaolinite, which also has a 7 Å spacing between its layers).

In view of the variation in grain size, mineral crystallinity, structure and chemistry, analyses of clays should be regarded as semi-quantitative. This is especially true with tropical soils in which non-diffracting ('amorphous') iron/aluminium oxides and poorly crystalline alumino-silicates (e.g. allophane, imogolite) occur. Numerical deficiencies in clay mineral totals determined by X-ray diffraction and by major element analyses often occur. Semi-quantitative analytical diffraction methods using either internal or external standards are reviewed by Brindley (1980). Selective dissolution methods are also useful for determining amounts of individual clay minerals (Page *et al.* 1982), although the effects of some treatments on the residual constituents are often unknown.

5.9.4. Thermal analysis of clays

Thermo-analytical methods are useful in the study of clays, providing information which is complementary to that obtained by X-ray diffraction, as various physical and chemical properties contribute to the results obtained. Several techniques are involved, the most common being differential thermal analysis (DTA), differential scanning calorimetry (DSC), thermo-gravimetry (TG) and evolved gas analysis (EGA). In DTA the difference in temperature between a sample and a known reference material is measured while the two are subjected to a controlled temperature programme (Mackenzie 1970, 1984). DSC measures the difference in energy input between a sample and a reference material as both undergo the same controlled temperature programme; the energy is measured either as a heat-flux or by the amount of power required to compensate for endothermic and exothermic reactions (Mackenzie 1980, Paterson 1981). In TG, changes in the mass of a sample with increasing temperature are recorded, usually as an integral curve although this may be converted to a derivative thermo-gravimetric (DTG) curve by differentiation (Redfern 1970). EGA records the nature and amount of gas evolved by a sample during a controlled temperature programme. Lombardi (1980) gives recommended methods of presenting these various types of temperature curves. Some types of apparatus allow results from two or more methods to be obtained simultaneously. Further details of sample preparation, chemical pretreatment, control of the composition of the atmosphere in the furnace, heating rates etc, are discussed by Paterson & Swaffield (1987).

TABLE 5.7. *Temperatures of endothermic and exothermic DTA peaks characteristic of clay minerals*

Clay mineral	Endothermic peak (°C)	Exothermal peak (°C)
Kaolinite	500–600	900–1000
halloysite	100–150	900–1000
	500–600	
chrysotile	700–750	800–850
smectites and	100–250	800–900
vermiculites	700	—
illites	150–200	—
	500–700	—
chlorite	500–600	750–850
palygorskite	100–150	—
	400–450	—
sepiolite	100–150	850–900
	300–350	—
gibbsite	300–350	—
goethite	—	550
carbonates	500–800	—

Clay minerals of the kaolinite, chlorite, gibbsite, goethite and carbonate groups have characteristic thermal curves, although some variability may arise due to differences in particle size. Groups with greater variability of chemical composition, such as smectites, vermiculites and illites, are more difficult to identify. Although DTA has been widely used to characterize poorly crystallized minerals (e.g. allophane) it is not a good diagnostic method for such materials. Table 5.7 gives the temperatures of endothermic and exothermic reactions typical of certain clay minerals.

5.10. Drilling and sampling

5.10.1. Introduction

Drilling and sampling practice is reviewed on a world wide basis by Brand & Phillipson (1985). Selection and description of samples should be related to the field classification system discussed in Chapter 4.

Tropical residual soils are usually non-homogeneous and anisotropic, making representative sampling particularly difficult. Large samples are desirable to ensure that grading, structure and fabric are representative. The coarseness of some residual soils may prevent the acquisition of small intact samples for laboratory testing and even with large samples, several may be required to cover the random variation which may be present in the ground even over short distances.

5.10.2. Drilling

All common methods such as augering, cable percussion, washboring and rotary drilling are employed. The bonded nature of most residual soil allows the use of rotary coring provided that large core sizes are used with careful drilling techniques. Boring to rock is usually required in site investigations, and hard and soft materials are often penetrated as unweathered rock is approached. As rotary drilling methods are usually required at this stage the use of rotary coring or washboring techniques in the upper layers of a residual soil becomes attractive.

The use of water flush in coring causes erosion and loss of core. Mud, air and special drilling fluid may be used, as discussed in relation to sampling in Section 5.10.3, below. Double or triple core barrels are generally used to improve core recovery.

In dry residual soil above the water table, augered or hand dug shafts of sufficient size for man-access are useful. These offer an effective alternative to drilling for visual inspection of the soil profile, for taking hand-cut samples and sometimes for undertaking in situ plate tests on the base or sides of the shaft.

5.10.3. Sampling

Samples may be taken for ground recognition or for the investigation of in situ soil or for evaluation of the soil as fill. They may also be required for testing for water content and density determination only or for laboratory testing of strength and stiffness.

Samples may be considered as either disturbed where the original structure has been destroyed by sampling, or intact when the original structure has been retained, although the sample may have been subjected to some disturbance. Intact samples may be taken in tubes, by rotary drilling or by cutting by hand from trial pits and excavations.

Residual soils are generally weakly bonded and behave as 'cohesive soils' during sampling hence the sampling methods for clay soils are appropriate. However, there is one important difference between the sampling of saturated clays and of residual soil. A saturated clay is generally able to retain a significant capillary suction without de-saturating. Thus, when a sample is taken from the ground and is at zero confining stress, it is able to remain saturated with a substantial pore water suction operating within it. If during sampling it has not had access to water which enables it to swell it will remain at the same water content as in the ground and will not suffer volumetric strain during sampling. This will not apply if a soil is partly saturated, as is often the case with residual soils. In such materials volumetric expansion is inevitable during sampling. Even if a residual soil is saturated, its structure generally contains relatively large voids which do not allow it to maintain a large pore water suction without de-saturating. Thus saturated residual soils are also likely to suffer volumetric expansion on sampling, even if they are sampled at constant water content.

Residual soils generally have a brittle structure and may suffer irreversible damage due to volumetric expansion even when samples are taken very carefully. This is supported by comparison between the results of laboratory tests, in situ tests and full scale loading (Sandroni 1985a, b; Vaughan *et al.* 1988). The extent to which discrepancies between laboratory tests and field observations still persist when the strains are measured correctly in laboratory tests (Vaughan 1985) is a matter of current uncertainty.

For the above reasons, some damage to the structure of residual soils is likely even if samples are cut by hand with great care. Damage is most likely in samples from depth, as the stress changes on sampling are large. Results of tests on such samples may therefore underestimate the true stiffness and strength of the in situ material.

Similar effects will occur around boreholes and trial shafts and may influence the results of in situ tests.

As damage to the soil structure may take time to occur (Vaughan *et al.* 1988), testing should be carried out as quickly as possible after stress relief has occurred both in the laboratory and in situ.

Sampling in driven or jacked tubes involves shear strain in addition to the volumetric strain described above. Such strains are inevitable, even when thin-walled samplers of large diameter are used, and further damage to the structure of the soil will result.

5.10.4. Sampling for density, water content and particle size measurement

Sampling in driven or jacked tubes is generally adequate for soil recognition, including fabric, and for density measurement. Sample disturbance is unlikely to result in errors in density of more than about five per cent, although the quality of the sample is important and density measurements on samples showing obvious structural damage should be treated with caution.

Tube samples are a convenient method of obtaining samples at constant water content, provided that they are taken from 'dry' boreholes. Such samples are likely to retain approximately the same pore water suction as existed in the ground and measurement of this suction in the laboratory is thus relevant to the in situ state (Richards 1985).

Disturbed samples are adequate for particle size determination, for compaction tests, and sometimes for water content determination. They should be large enough for a representative grading to be present. Disturbed samples for particle size analysis should contain a dry mass of soil sufficient to comply with Clause 1.5.4.2 (5) of BS 1377: 1975, which relates sample size to the largest significant particle size.

For compaction and CBR tests, sufficient material should be taken to allow for separate tests batches, on the assumption that particle degradation will occur and an unrepresentative grading will result if material is used more than once.

Water contents of soils above the water table may often be determined from disturbed samples, particularly when the degree of saturation is low. Disturbed samples for water content determination should be taken from at least 30 mm behind or below a freshly exposed face and not from the surface. The risk of drying or wetting prior to sampling should always be considered however.

5.10.5. Sampling for the laboratory determination of strength and stiffness

Testing of disturbed material is generally acceptable for residual soil for use as fill, provided that the influence of water content in the potential borrow pit and its possible seasonal variation is taken into account. However there may be some differences in structure between samples compacted in the laboratory and in the field (de Mello 1980) and for major works samples taken from a trial fill are preferred.

The determination of strength and stiffness in the laboratory requires high quality samples. Generally, hand-cut samples from trial pits and shafts are used. Tube samples are not usually suitable for this purpose, except perhaps when the soil has a high clay content (Richards 1985). Cores from rotary drilling may be adequate provided that large diameter cores are taken. The drilling fluid used is important. Water or mud causes swelling of the core and exacerbates the problems of sample disturbance described above. Air as a drilling fluid avoids this problem, at least above the water table, but as it causes changes in soil suction and effective stress through drying it is not recommended in desiccated soils where the determination of suction is required (Richards 1985). The use of drilling foam in rotary drilling is a relatively recent development (Phillipson & Chipp 1982; Brand & Phillipson 1984; Phillipson & Brand 1985).

5.10.6. Block samples

The highest quality intact samples are obtained by block sampling from exposures in trial pits and trenches. Stepped construction of the pit or trench provides convenient benches for cutting and trimming samples.

A procedure for preparing and removing hand-carved block samples is illustrated in Fig. 5.8. For soils with a sensitive structure the block should be encased in its box immediately after trimming and the exposed faces coated before attempting to undercut for removal. The box should be packed with damp sawdust or plastic foam (Dearman & Turk 1985) to support the sample during transit.

Block samples should normally be at least six times larger than the largest particle present. However, a sample which is too heavy to lift comfortably is more likely to suffer damage than one which can be handled with ease. Therefore unless larger samples are essential blocks should not normally exceed 200 mm cube, perhaps with a trimmed length twice the diameter to give a sample suitable for triaxial testing.

An alternative method for taking intact samples from soils free of gravel sized particles is to use the core cutter procedure described in Test 15(D), BS 1377: 1975. This may also be used for friable soils with little cohesion or for soils with a very sensitive grain structure. The cutter should not be hammered into the ground. Instead a cylindrical block should be roughly trimmed in the ground, leaving about 10 mm all-round to be pared off as the core cutter is jacked down steadily. The technique is illustrated in Fig. 5.9. An intact sample may be taken by the same method in a CBR mould if the mould is fitted with a suitable cutting shoe.

Where the soil is suitable an undisturbed sample for compression testing can be taken by hand in a plastic or metal tube, typically 100 mm diameter and 200 mm long. The tube should be provided with a cutting edge and lightly greased interior. The tube is gently eased down over the soil which has been carefully prepared to leave only 1 or 2 mm to be pared off, keeping the axis of the tube vertical. For small test specimens (e.g. 38 mm diameter) the risk of disturbance can be reduced by fitting a rubber membrane around the soil, trimmed to size, before removal.

Mori (1985) described a method of taking block samples by driving long nails in a circle through a template. He also described ground freezing for sampling residual soils in Japan, but freezing and thawing can cause sample disturbance.

5.10.7. Protection of hand-cut samples

During sampling operations the location as well as the samples themselves should be protected from the weather. Large umbrellas may be used to shade them from direct sunlight and to reduce drying out. Protection from wind and rain may also be necessary.

When trimming the face of an undisturbed sample the final 20 mm or so should not be removed until immediately before that face can receive a protective coating. Alternate layers of muslin cloth and molten paraffin wax provide the usual protective wrapping.

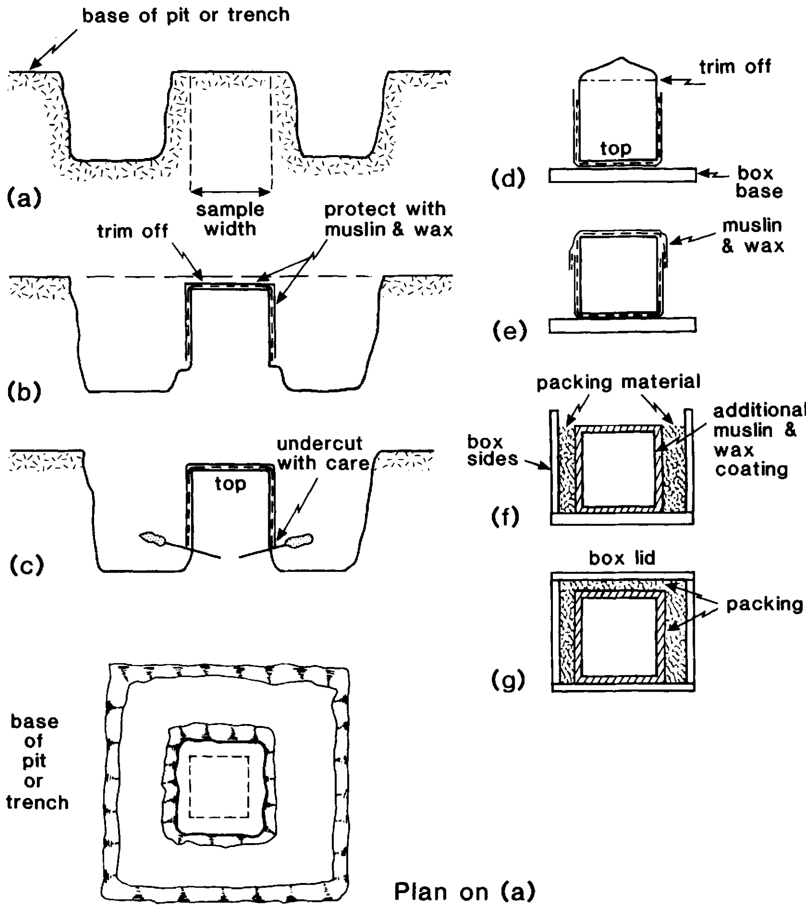


FIG. 5.8. Stages in taking and protecting a block sample.

Cling-film and aluminium foil are also used, but the latter should not make direct contact with the soil.

After waxing, block or core samples should be wrapped and sealed in polythene bags, enclosing some damp cloth or paper to provide local humidity as waxes are not completely impermeable to moisture.

Allowances should be made for the possible effects of seasonal changes on the state of the soil when sampled, especially desiccation during a dry season.

5.11. In situ tests

5.11.1. Introduction

In situ tests are used extensively in residual soils. They are often convenient, they can sense the properties of relatively large volumes of soil, which helps deal with the local heterogeneity common in residual soils, and they may be performed on soil which has been less disturbed than a sample removed to the laboratory.

They may be considered in two categories. First, there are the simple exploratory tests such as dynamic and static penetrometers which sense the hardness of the soil, but which can only be used to derive engineering parameters through empirical correlations based on experience. Second, there are tests such as the plate and pressuremeter, from which engineering parameters can be derived directly. Of the various tests which may be employed only the most commonly used are considered here.

The successful use of the first category of the test to derive engineering parameters depends on the recognition and classification of the type of soil in which the test is performed, as empirical correlations cannot be transferred from one type of soil to another. It also depends on the quality and amount of data from which the empirical correlation used to interpret the test has been derived. The success of the second type of tests depends on the experimental errors intrinsic to the method, on the extent to which the ground tested has been disturbed by drilling or

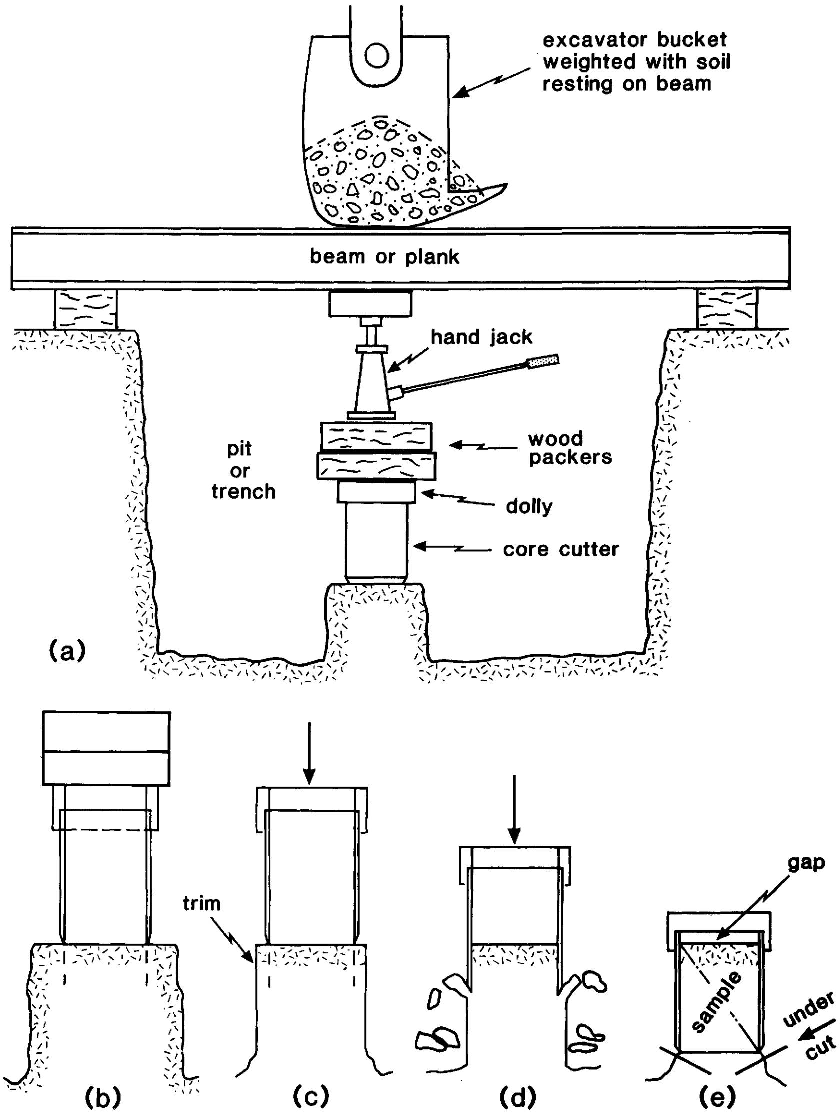


FIG. 5.9. Jacking undisturbed core-cutter sampler.

excavation, on the extent to which the parameters measured are relevant to the problem, and on the extent to which the theory used to interpret the results is correct.

As discussed in Chapter 6, residual soils have properties which are essentially different in many ways from those of sedimentary soils. Interpretations of in situ tests are often based on sedimentary soils and their application to residual soils requires caution unless they are validated by extensive field experience. It is quite likely that interpretations based on sedimentary granular soils will be conservative if applied to residual soils of high density and unconservative if applied to residual soils of low density.

5.11.2. Penetrometers

Dynamic Penetration Tests. The most common test is the Standard Penetration Test (SPT), which is useful for examining variability of soil conditions across a site (de Mello 1972). Tan (1986) described its use in Malaysia. Very few correlations have been published linking engineering behaviour directly to SPT blow count, '*N*'. A common practice in Brazil is to convert *N* to a Static Cone point resistance and to use this in foundation design (Sandroni 1985b) according to standard methods. Martin (1977) gave a correlation between *N* and the Menard Pressuremeter modulus for residual soils from the Piedmont area of the USA, derived from gneiss, schist and granite. He also provided evidence that settlements of structures on these soils can be predicted reasonably well using a modulus for the soil equivalent to the pressuremeter modulus. Other correlations between blow count and stiffness modulus determined in various ways are discussed by Chang (1988), Massey & Pang (1988) and Rocha & Carvalho (1988).

Other types of dynamic penetration test using lighter equipment include the JKR probe, described by Mun (1985), which is used extensively in Malaysia for preliminary investigations and for designing foundations for light structures. Mun gave a correlation between blow count and allowable bearing capacity. Phillipson & Brand (1985) described a similar light cone apparatus, the GCO Probe, in use in Hong Kong and Pitts *et al.* (1985) report a similar device used in Singapore. Malomo (1986) described the use of the same equipment in Nigeria.

Static cone penetration tests. The development of the electric cone has increased the use of the static cone penetrometer in site investigation generally. It is used in residual soils, although most experience is with the mechanical cone rather than with the SPT. Correlations between cone resistance and SPT blow count are discussed by Chang (1988) and Rocha-Filho & Carvalho (1988).

5.11.3. Plate tests

Plate tests are used in residual soils for the determination of stiffness parameters for foundation design, as reported by Lacerda *et al.* (1985) who also give some comparable data for the settlement of full size foundations. A feature of their results is that soil stiffness increases with the size of loaded area, in the same way as occurs for plate tests on granular sedimentary soils. These relationships are discussed by Vargas (1979) and Rocha & Carvalho (1988). Rocha & Celso (1983) give detailed results for plate tests of different diameters on residual soil from gneiss which also show these effects.

Plate tests will usually involve drained loading, due to the relatively high in situ permeability of residual soils. The results of plate tests will be influenced by the pore water suctions in the ground being tested and a reduced suction may operate below a structure to which the results of a plate test may be applied.

Plate loading tests on residual soils generally show a yield stress, above which increasing settlement is observed. As yet there is no theory which can be used to examine the way weakly bonded soil yields under loaded plates and spread foundations. Yield seems to depend on the lateral stress in the ground immediately under the plate after excavation to the depth of the test (Vaughan 1988), but there is some evidence to indicate that the yield stress observed below a plate is similar to that observed in the same soil if a distributed load is applied to it. It may therefore indicate a safe bearing pressure. This is discussed by Chin (1988), Rocha & Carvalho (1988) and Sweeney & Ho (1982).

5.11.4. Pressuremeter tests

The pressuremeter can be used conveniently in most residual soils, either in a pre-bored hole (Baguelin *et al.* 1978; Pavlakis 1980; Barksdale *et al.* 1986) or in the self-boring version (Smith 1985). The latter minimizes ground disturbance prior to testing.

As with the plate test, there is at present no developed theory by which results can be interpreted. Pavlakis (1980) gave test curves for the Menard pressuremeter and Smith (1985) gave test curves for the Cambridge self-boring pressuremeter. Both show a pronounced bi-linearity of the pressure against displacement curve. The change in gradient occurs at a pressure which is too high to be related to original *in situ* lateral stress and implies a tensile hoop stress at the borehole wall.

Barksdale *et al.* (1986) found good agreement between measured settlements of actual structures and those predicted from pressuremeter tests using the empirical relationships of Baguelin *et al.* (1978) for first loading. Predictions assumed that the modulus of the ground was equal to the average modulus deducted from the pressuremeter results and simple 'elastic' settlement theory was used. Pavlakis (1980) cautioned against over-reliance on pressuremeter data in anisotropic materials.

Other discussions on the use of the pressuremeter are given by Rocha & Carvalho (1988) and Chang (1988). Blight (1988) discusses the uses of the pressuremeter in predicting the failure load and settlement behaviour of piles and reports success when using simple procedures derived from experience with other soils.

5.11.5. Permeability tests

The permeability of residual soils may be measured in the laboratory and in the field. There is general agreement that measurement in the field is required to give fully representative results. Permeabilities are usually fairly high, which makes borehole tests easier to perform. There may be difficulty in sealing packers and tests may be performed more reliably on borehole standpipe piezometers if head losses in the piezometer tip and the filter material used are controlled. The influence of partial saturation on permeability needs to be taken into account in interpreting results as long-term inflow tests are likely to give permeabilities which are close to those for the saturated soil.

6. Guidelines to engineering properties and characteristics

6.1. General

Engineering in tropical residual soils is often straightforward, and may be based successfully on experience (Brand 1982, 1985). However as the principles of the engineering science of soil mechanics have been developed for sedimentary soils, they are often inappropriate for residual soils and cause confusing results when they are applied to such materials. Residual soils exhibit special engineering properties and characteristics which differ from those found in sedimentary soils as a result of the predominant role of weathering in the genesis of the soil. Thus they apply to the whole weathering profile, not merely to the upper fully-weathered layers. Some of these special characteristics are summarized here.

Residual soils often exist where the current climate has induced deep desiccation or where there is severe seasonal wetting and drying. Effective stress changes seasonally and when surface evaporation is impeded these changes can produce large strains in the superficial soil. In addition the surface layers of soil may be more chemically active than is usual for sedimentary soils.

6.2. Residual soils in situ

The following characteristics of in situ residual soils are considered

(a) mineralogy;
(b) variable structure and the presence of bonding between particles;
(c) variable void ratio unconnected with stress history;
(d) permeability often unrelated to particle size and grading;
(e) discontinuities of low strength;
(f) partial saturation, which frequently occurs to considerable depth in these soils.

6.2.1. Mineralogy

The mineralogy of residual soils varies considerably being partly inherited from the parent rocks or soil from which they are derived and partly due to the weathering processes involved in their genesis. As a consequence the unit weight of the particles present in residual soil may also vary more than is usual in sedimentary soils (see Section 5.2.8 and Table 6.1).

Clay minerals are usually present. Generally these have been created by weathering, but they may also be inherited from the parent rock if mudrocks and sedimentary clays have been weathered.

Smectites are often found in vertisols. If present in quantity these active clay minerals can cause important volume changes in response to small changes in effective stress. Large heave movements result when desiccated soils rich in smectite wet due to the influence of engineering works. A change in surface evaporation, such as results from creating a sealed road surface, would be sufficient to cause such movements. Soils of this kind may also experience large vertical movements between the wet and dry seasons as soil water suctions change and may be subject to deep cracking when desiccated.

Kaolinites occur in many residual soils, particularly in fersiallitic, ferruginous and ferralitic profiles. Kaolinites are similar to smectites in that they are usually platey in shape with a low coefficient of interparticle friction, but the particles are much larger and less active. Thus a soil containing kaolinite has a higher strength and a lower compressibility than a soil of the same clay fraction containing smectite. The crystal form of kaolinite is likely to be variable, and thus the engineering properties which depend on particle shape will also vary.

Platey clay minerals with a low coefficient of friction such as smectite and kaolinite can orientate when shearing occurs (Lupini, Skinner & Vaughan 1981). This gives rise to a low residual frictional strength and to polished shear surfaces. Such surfaces may be formed in the in situ soil by the strains accompanying soil genesis, shrinkage and swelling.

The engineering behaviour of a soil containing platey clay minerals as well as coarser rotund grains formed from non-clay minerals, depends on the amount of clay present (Lupini *et al.* 1981). Typically, a soil with less than 15% clay content behaves much as a granular material. No orientation of the platey clay minerals during shear is possible and a unique value of φ'_{CV}, the friction value during shear at constant volume, is obtained at large strains. A soil with more than 40% clay content has properties dominated by the presence of the clay. In such a soil the platey clay minerals can orientate and a continuous shear surface form. While there is a value of ϕ'_{CV} operating during shear at constant volume with random particle orientation, this is only a transient state. At large strains a shear surface of orientated clay forms, and the friction angle drops to a lower residual value, ϕ'_R. At intermediate clay contents the shear behaviour is transitional between these two states.

TABLE 6.1. *Typical void ratios of Brazillian residual soils (after Sandroni 1985b)*

Parent rock	Unit weight of grains ($g\,cm^3$)	Void ratio
Gneiss	2.60–2.80	0.30–1.10
Quartzite	2.65–2.75	0.50–0.90
Schist	2.70–2.90	0.60–1.20
Phyllite & Slate	2.75–2.90	0.90–1.30
Basalt	2.80–3.20	1.20–2.15

In addition, clay minerals may be coated with other materials which may significantly change their properties.

Clay minerals such as halloysite and allophane are frequently present in residual soils and are fundamentally different from smectite and illite, for example, which are found in sedimentary soils. They are not platey in shape and they do not give low peak or residual strengths, or form low-strength discontinuities after shear to large strains. They also exhibit low swelling moduli and small strains when subject to wetting and drying. Despite their small size, they behave in a manner more commonly associated with silt and sand sized particles. Although clay particles of this kind can contain water within their solid structure (Terzaghi 1958), this is inert and has no influence on mechanical behaviour. Such soils may have unusually low dry unit weights and index properties which fall well below the A-line on the standard classification chart (Wesley 1973).

Clay mineralogy also influences drained shear strength, as exemplified by the angle of shearing resistance, φ'_{CV}, of the destructured soil sheared at constant volume. This is the strength observed in a test on a sample of the soil normally consolidated from a slurry. In a soil deficient in platey clay minerals, it is also the residual strength (Lupini *et al.* 1981). If sufficient such minerals are present at large strains the strength will drop to a lower residual value, ϕ'_R. Table 6.2 gives typical values for soils in which clay minerals predominate (Wesley 1977; Lupini *et al.* 1981; Boyce 1985).

The coarser grains of residual soils are usually

TABLE 6.2. *Angles of shearing resistance according to clay mineralogy (for soils in which the clay minerals present dominate the shearing mechanism)*

Clay mineral	φ'_{CV}	φ'_R
Smectites (senstive to type and clay water chemistry)	15–20°	5–11°
Kaolinites (sensitive to crystal form)	22–30°	12–18°
Allophane	30–40°	30–40°
Halloysite	25–35°	25–35°

inherited from the parent rock. They may include relatively hard and unweathered quartz, or partly weathered and weakened material derived from feldspars, etc. Such weak particles may degrade readily during shear, and the soil may then have a rather unstable grading. The grading of the soil obtained by sieving may itself depend on the energy used during sample preparation.

The intrinsic compressibility/expansibility of particulate soil is represented by the compression index, C_C, for the normally consolidated soil in one-dimensional compression and by the similar index for swelling, C_S. The variation of these indices according to clay mineralogy is discussed by Lambe & Whitman (1969). In natural soils the values will depend on the amount of the clay mineral present.

These values are not directly applicable to in situ residual soil as compressibility is controlled by the bonded structure of the soil.

6.2.2. Structure and inter-particle bonding

The structure of residual soil is largely the result of the weathering processes by which it is formed. Structure frequently involves a wide range of pore sizes, some being larger than would normally be associated with the grading and grain size of the soil.

There is usually some inter-particle bonding in residual soils. With moderate degrees of weathering, some may be inherited from the parent rock, but in a fully developed residual soil it is more likely to be due to the effects of crystallization during weathering and mineral alteration, and to the precipitation of cementing material (Terzaghi 1958; Newill 1961; Wallace 1973). In the extreme, represented by various forms of duricrust, cementation may give sufficient strength for a rock-like material to be re-formed but in most residual soil the bonding is much weaker. It should be noted, however, that even a bond so weak that a sample can scarcely be handled still provides a component of strength and stiffness which will have a strong influence on engineering behaviour.

The effects of a bonded structure are as follows

(a) The soil exhibits a yield stress. This is defined as a stress or stress state at which there is a discontinuity in stress–strain behaviour, and a decrease in stiffness. This effect is illustrated on Fig. 6.1 (a) (Vargas 1973). The yield stress is similar to that of an over-consolidated sedimentary soil. Indeed, the yield stress observed in the oedometer is often referred to as a quasi-pre-consolidation pressure but it is related to structure and bonding and not to stress history (Wallace 1973). The yield may be generalized in stress space (Sandroni 1981; Vaughan & Kwan 1982; Vaughan 1985, 1988; Vaughan *et al.* 1988). Two examples are given on Fig. 6.2.

(b) The soil also exhibits a peak shear strength envelope in terms of effective stress which has a

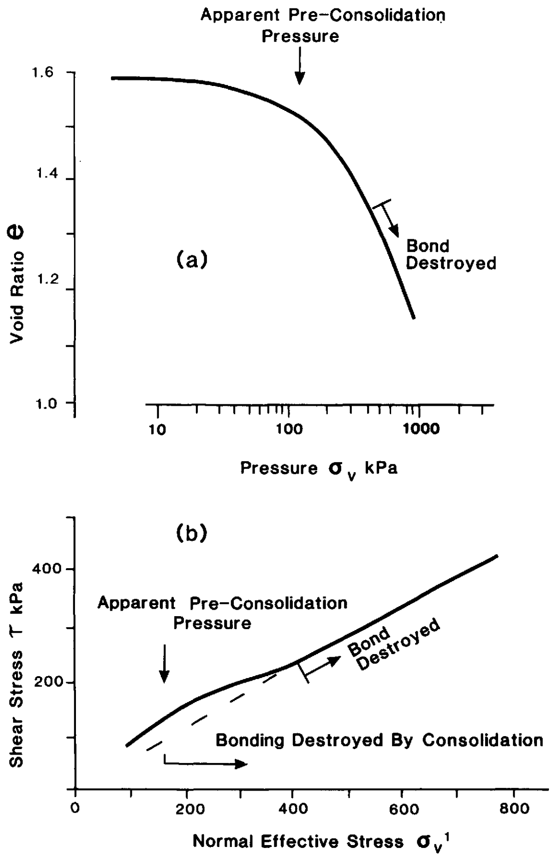


FIG. 6.1. Apparent pre-consolidation pressure (Vargas 1973); (a) observed in the oedometer; (b) influence on drained shear strength in direct shear.

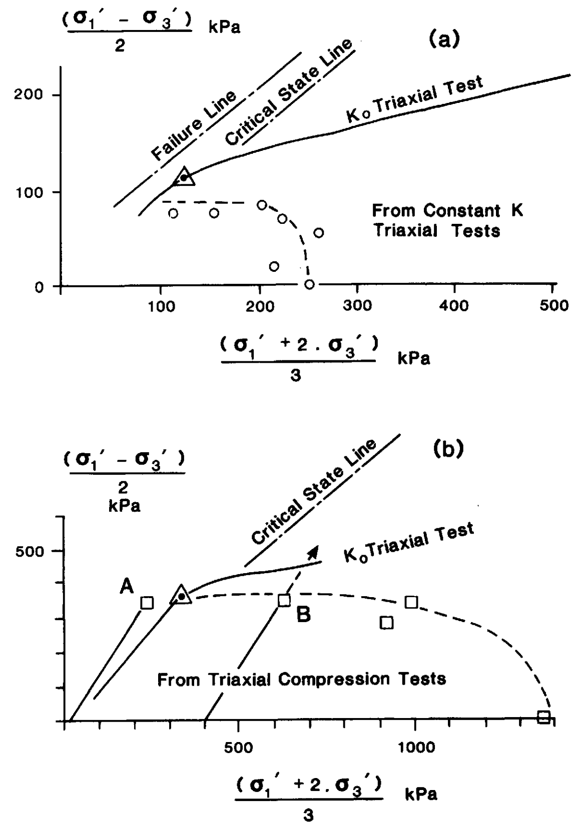


FIG. 6.2. Yield stresses observed in tests on residual soils; (a) residual soil from gneiss (Sandroni, 1981); (b) residual soil from basalt (Vaughan *et al.* 1988).

cohesion intercept. This is due to structure and bonding rather than to density and dilation (although the latter may also be present) and is unrelated to density. It is this property which often allows relatively steep slopes to remain stable (Wesley 1977; Vaughan 1985). The connection between yield and strength is illustrated on Fig. 6.1 (Vargas 1973) and an example of this component of strength as a function of bonding rather than density and dilation is shown on Fig. 6.3. The results of two drained triaxial tests on weathered basalt are shown. The yield points for these tests are shown on Fig. 6.2(b). At the low confining pressure the peak strength is reached while the sample was still contracting, not at the point where the rate of dilation was a maximum, as would have been the case with an unbonded soil.

(c) Once the soil has exceeded its yield stress its bonding is progressively destroyed as relatively large strains occur. As this occurs its porosity will tend towards that which the same soil would have at the same stresses in an unbonded 'destructured' state. This leads to the dependence of post-yield deformation on yield stress and initial porosity, rather than on the intrinsic compressibility of the 'de-structured' soil.

(d) The structure and particularly the inter-particle bonding are sensitive to disturbance during drilling and sampling and may easily be damaged, as discussed in Section 5.

(e) Inter-particle bonds may also be damaged by the strains imposed during the initial stages of shear testing, if the type of test and the stress paths involved cause significant strains prior to failure. Strength and yield stress are then underestimated.

(f) The use of full strength and yield stress for the completely undisturbed material may not be appropriate for soils at shallow depth which have been subject to stress relief in engineering works, disturbances by excavation and compaction, etc. Schmertmann (1969) discusses a case where swell potential in a stiff clay below a foundation was increased by destruction of the soil structure by excavating plant and compaction.

(g) Changes in stress and strain when swellable soils containing smectites are subject to wetting and drying

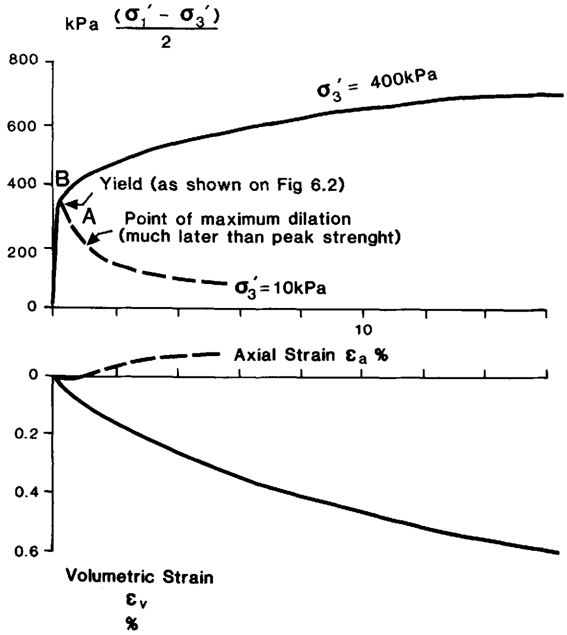


FIG. 6.3. Drained triaxial tests on residual soil from basalt.

cycles may well be sufficient to destroy structure and bonding.

The deformation of in situ residual soils will be small unless the yield stress is exceeded. Thus the determination of yield stress is of great importance. Yield can only be demonstrated by a discontinuity in stress–strain behaviour when this is plotted on linear scales. The use of log–log scales may facilitate the demonstration of yield (Vaughan 1985, 1988), Fig. 6.4. Plots of strain or void ratio against log (stress), commonly used for for the oedometer test, do not show yield clearly and indeed may indicate a fictitious yield where none has occurred (Vaughan 1985). The determination of yield in the laboratory is subject both to the stress path adopted and to the effects of sample disturbance. The stress path for a bonded soil loaded in the oedometer is different from that of a sedimentary soil. Bonding gives a steep stress path to the point at which bonding starts to break down (Fig. 6.2 and Vaughan 1985). The stress path then migrates towards that for the un-bonded and de-structured soil ($K_0 = 1 - \sin\varphi'$) as the bonding is removed.

The determination of yield stress by means of in situ tests is subject to how the test is interpreted, and also to effects of ground disturbance prior to testing. The problems of laboratory and in situ testing are discussed more fully in Section 5. Yield in prototype loading will depend on the stress path applied to the soil. Thus there is advantage if the stress path of the test approximates to that of prototype loading. Table 6.3 summarizes some typical yield stresses for different types of loading. It should be borne in mind that yield stresses determined in the laboratory are probably underestimated due to the effects of sample disturbance. The oedometer test substantially underestimates yield pressures in the field (Prusza *et al.* 1983; Dib 1985); as summarized in Table 6.3.

Residual soils may develop a strongly anisotropic

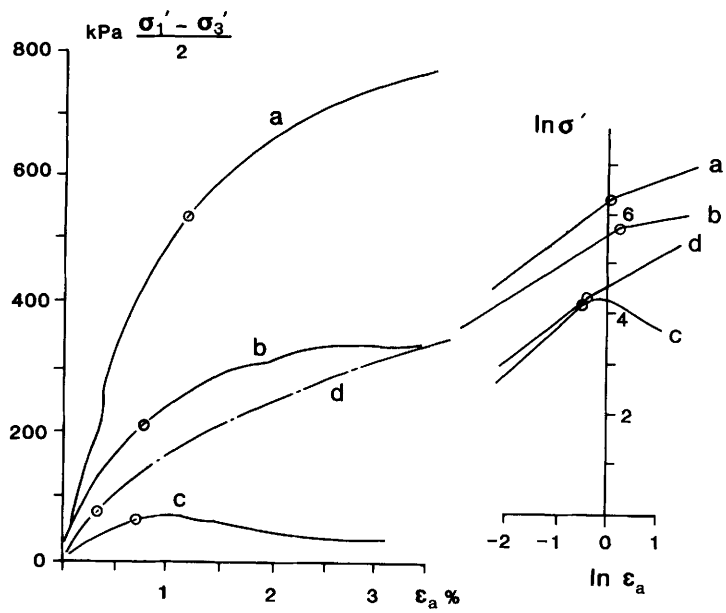


FIG. 6.4. Yield in laboratory triaxial tests shown by plots at natural and log–log scales. (a)–(c) Drained compression tests on soil from basalt. (d) Constant stress ratio tests, $K = 0.45$, on soil from gneiss (after Vaughan 1988).

TABLE 6.3. *Yield stresses observed in residual soils*

Type of observation and soil	Yield stress (kPa)	Reference
Oedometer and K_0 triaxial tests		
Papua New Guinea: Halloysite and Allophane	100–350	Wallace (1973)
Volcanic Clay	110–270	Gradwell & Birrell (1954)
Brazil: Gneiss, Basalt and Sandstone	60–450	Vargas (1953, 1973)
Brazil: Granite, Basalt and Sandstone	50–200	Dias & Gehling (1986)
SE United States	100–550	Sowers (1963)
Japan: Allophane and Halloysite	200–550	Koizumi & Ito (1963)
USA: Granite, Gneiss and Schist	50–150	Barksdale *et al.* (1975)
Brazil (PUC-RJ): Gneiss	150–500	De Britto & De Campos (1980)
Brazil (Tuccarui)	50–150	Dib (1985)
Venezuela (Guri): Gneiss	50–300	Prusza *et al.* (1983)
Mauritius: Basalt	900	Vaughan *et al.* (1988)
Indonesia and New Zealand: Volcanic Ash	200–500	Wesley & Matuschka (1988)
Isotropic stress tests		
Brazil (PUC-RJ): Gneiss	200–550	De Campos (1980)
Mauritius: Basalt	1400	Vaughan *et al.* (1988)
Plate loading tests		
Venezuela (Guri): Gneiss	300–500	Prusza *et al.* (1983)
Brazil (PUC-RJ): Gneiss	250–300	Rocha & Celso (1983)
Field loading (increase in overburden pressure)		
Brazil (Tuccarui): Various	300–400	Dib (1985)
Venezuela (Guri): Gneiss	300–500	Prusza *et al.* (1983)
New Zealand (New Plymouth): Volcanic Ash	100	Wesley & Matuschka (1988)

structure inherited from the parent rock. This is common in soils from metamorphic rocks and the effect is increased when mica is present. Table 6.4 shows some typical strength measurements in such a soil (Sandroni 1985b).

6.2.3. Void ratio

The void ratio of residual soils may vary widely, independent of the source rock, the type of weathering and the stress state. This may be due to variations in the amount of the weathering products which have been leached from the soil (Lumb 1962). Typical void ratios for residual soils from Brazil are given in Table 6.1 (Sandroni 1985b). Void ratio is a function of the weathering process and is not related to stress history.

In a weakly bonded soil the void ratio has a strong influence on drained strength, which increases with dry density (Howatt & Cater 1985; Howatt 1988). It

TABLE 6.4. *Strength of anisotropic soil from micaceous gneiss (after Sandroni 1985b)*

Parent Rock	Macro-structure	Strength from direct shear box tests $50 < \sigma'_n < 500$ kPa: Parallel (to bedding)	Perpendicular (to bedding)	Water condition
Ferritic quartzite	Laminated (silty sand)	$c' = 20$ kPa, $\varphi' = 37°$	$c' = 50$ kPa, $\varphi' = 44°$	Partially saturated
Micaceous quartzite	Schistose (sandy silt)	$c' = 40$ kPa, $\varphi' = 22°$	$c' = 45$ kPa, $\varphi' = 27°$	Partially saturated
Migmatic gneiss	Banded	$c' = 40$ kPa, $\varphi' = 20°$	$c' = 52$ kPa, $\varphi' = 23°$	Partially saturated
Migmatic gneiss	Banded	$c' = 30$ kPa, $\varphi' = 21°$	$c' = 49$ kPa, $\varphi' = 22°$	Saturated

also influences deformation. This is best considered in relation to the behaviour of the same soil in the unbonded 'de-structured' state, as it is towards this state that the soil will trend as it is subjected to large strains (Vaughan *et al.* 1988). Void ratio at a particular stress may be in one of three states listed below in order of increasing intrinsic stability.

(1) Meta-stable or structure permitted, in which the natural soil exists at a void ratio which is impossible for the same soil in the de-structured state at the same stress level. It can exist in this state only due to the strength and stability provided by its inter-particle bonding.

(2) Stable-contractive, in which the soil could exist in the de-structured state, but would contract during shear towards the constant volume 'critical state'.

(3) Stable-dilatant, in which the soil could exist in the de-structured state at the same stress level, but where it would expand during shear towards the 'critical state'.

These characteristics are illustrated in Fig. 6.5. Bonding and void ratio combine to determine the strains which the soil will undergo when it yields at a particular stress state. If an in situ residual soil exceeds its yield stress (either in shear failure or due to increasing average stress: the 'pre-consolidation pressure' effect) then the strains which it will subsequently suffer depend largely on its state: if

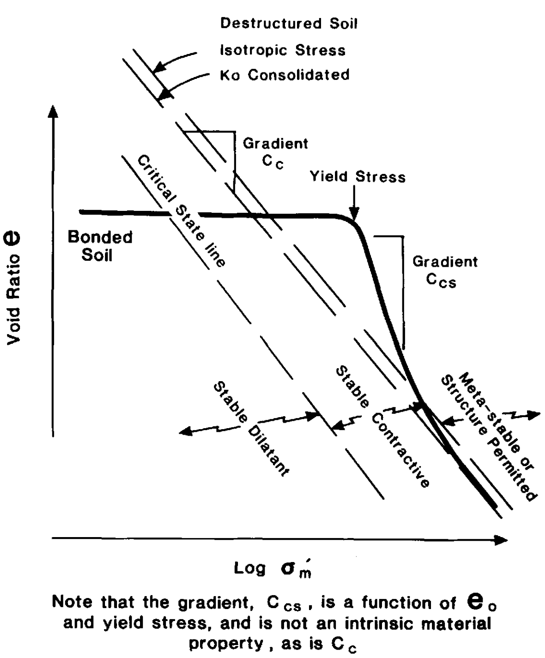


FIG. 6.5. Stress–void ratio state of a residual soil related to the states possible for the de-structured soil. Note that the gradient, C_{CS} is a function of E_0 and yield stress, and is not an intrinsic material property, as is C_C.

meta-stable it will be subject to large contractions, if stable-dilatant it will suffer only relatively small strains (unless shear failure occurs). Thus recognition of state allows the consequence of exceeding yield stress to be established. The slope of a void ratio/log stress plot from a one-dimensional or isotropic stress compression test after yield is approximately linear. The slope of this line is sometimes equated with the slope of the 'virgin' compression line for a normally consolidated sedimentary soil. However, for a residual soil this slope is a function of the yield stress and the initial porosity of the soil, as shown on Fig. 6.5, rather than being an intrinsic function of the grading and mineralogy of the soil. It has been found that the gradient of this line in residual soil, termed here as the parameter C_{cs}, is a function of initial porosity rather than soil type. This is in accord with the mechanism described above. Typical correlations are shown on Fig. 6.6.

If a soil with a relatively high degree of saturation fails undrained in a meta-stable state, then large pore pressures are likely to be generated, the undrained strength can be very low, and a flow slide can result.

Unloading and a reduction in mean effective stress can cause yield of a bonded structure when a soil contains minerals which swell and expand sufficiently to break the internal bonding. The presence of mica (Sandroni 1985) may cause this to happen, as well as the presence of active clay minerals (Leroueil & Vaughan 1990).

The state of an in situ soil according to the zones of Fig. 6.4 can be assessed by comparing in situ stresses and void ratios with the compression line for the remoulded and de-structured soil (Vaughan *et al.* 1988). It can be assessed approximately by relating in situ void ratio to the liquid limit and to the optimum dry density as determined in the standard compaction test (Vaughan *et al.* 1988), see Section 5. The use of void ratio (or the equivalent of saturated water content) is necessary in partly saturated soils when natural water content is independent of density.

The advantages of relating in situ void ratio to equivalent standard test values is illustrated in Fig. 6.7. A profile of the weathered Gneiss soil from Guri (Prusza *et al.* 1983; Vaughan 1988) is shown, together with void ratios equivalent to the liquid and plastic limits and the optimum dry density. From these it is possible to deduce the liquidity index and the relative void ratio (the equivalent to liquidity index with optimum water content substituted for plastic limit, see Section 5). The liquid and plastic limits have not been corrected for the removal of the coarse fraction of the soil. The uncertainty involved in using the plastic limit as a measure of consistency in soils of low plasticity is clear. The plastic limit suddenly increases at a depth of 10 m, giving an apparent decrease in liquidity index when all the other parameters indicate that the soil has become relatively more porous. The

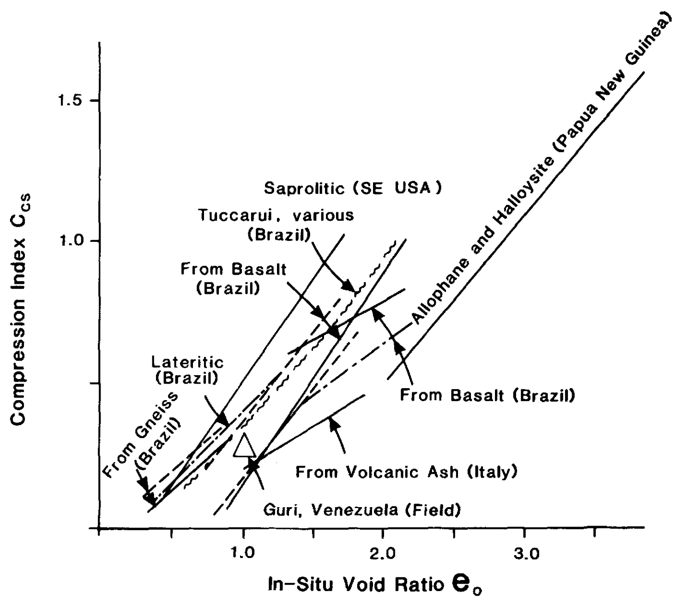


FIG. 6.6. Relationships between compression index, C_{CS}, and initial void ratio, C_0 (after Wallace 1973; Lacorda *et al.* 1985).

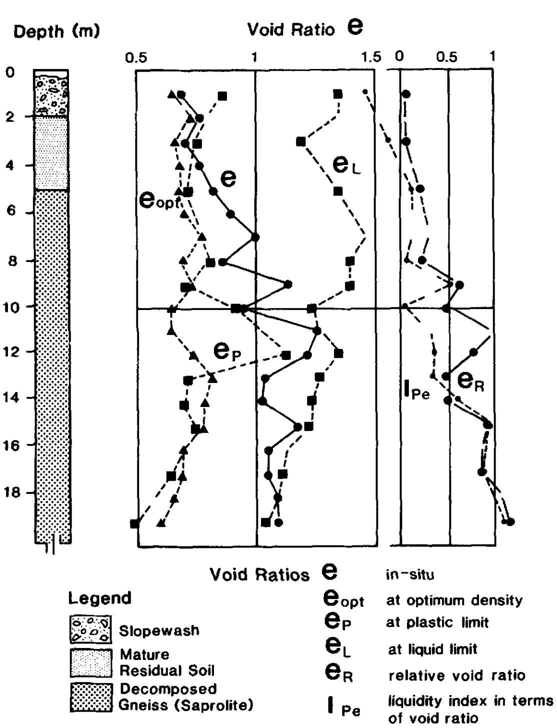


FIG. 6.7. Profile of weathered gneiss at Guri Dam, Venezuela, plotted in terms of void ratio (after Prusza *et al.* 1983).

latter is indicated by the relative void ratio. A plot of this kind indicates that in situ void ratio related to the consistency of the soil increases markedly with depth. Changes in void ratio with depth within a profile of weathered granite are discussed by Radwan (1988).

6.2.4. Hydraulic properties and permeability

Residual soils are likely to have high void ratios and some large macro-pores (Section 6.2.2), thus permeability may be much higher than would normally be associated with the grading of the soil. Superficially, residual soils may be cracked and fissured, with open flow passages further increasing permeability. In situ permeabilities in a soil which by grading and mineralogy is a clay may be as high as 10^{-4}–10^{-5} m s^{-1}. Some typical values are given in Table 6.5. Permeability does not normally decrease significantly

TABLE 6.5. *Typical values of permeability for in situ residual soils (after Costa Filho et al. 1985; Dearman et al. 1978)*

Soil type	Permeability (m s^{-1}) Young (saprolitic)	Mature
From granite	4×10^{-3}–5×10^{-9}	4×10^{-6}–5×10^{-9}
From gneiss	5×10^{-6}–1×10^{-7}	5×10^{-5}–1×10^{-6}
From basalt	—	3×10^{-6}–1×10^{-9}

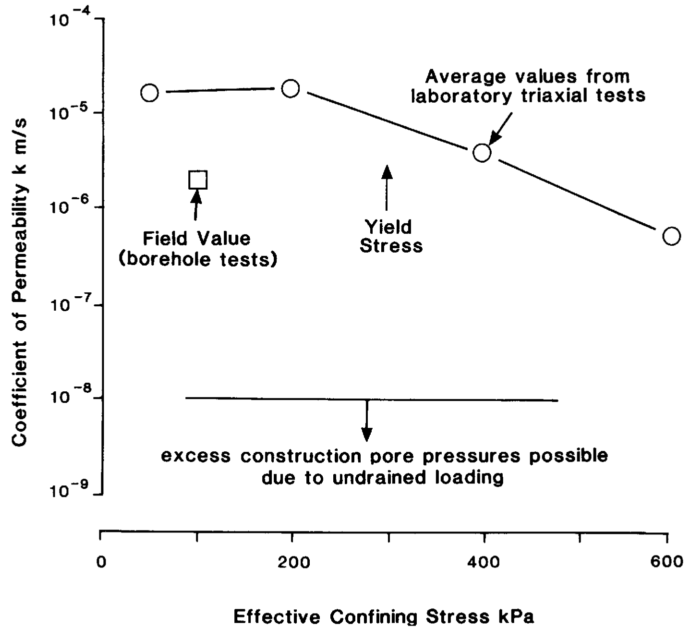


FIG. 6.8. Variation of permeability with confining stress: residual soil from gneiss at Guri Dam (after Medina & Liu 1982).

under loading until the yield is exceeded, when it may drop significantly. This effect is illustrated in Fig. 6.8, using data from Medina & Liu (1982).

One of the consequences of the high in situ permeability usually found in residual soils is that loading or unloading at normal engineering rates seldom results in undrained conditions. Thus excess pore pressures are not generated where loading occurs, such as in the foundations of embankments. Excess pore pressures may develop post-failure after slope failure in wet, porous soils (Vargas 1983), due to the collapse of porous structure. The temporary beneficial effects of undrained pore pressure depressed by unloading in cut slopes, as occurs in clays of low permeability, are unlikely. On the other hand, in partly-saturated soils, high pore-water suctions may persist during and subsequent to excavation.

Structural effects may give permeabilities which are unacceptably high for the foundations of water retaining embankments. The activities of termites and other insects can cause large diameter and potentially dangerous seepage passages in residual soils (Lemme *et al.* 1985; de Mello 1988).

In partially saturated soil the permeability depends on the degree of saturation. These relationships are discussed by Lee *et al.* (1983) and Morgenstern & de Matos (1975). The change in permeability with depth will influence the way in which pore pressures develop in a partially-saturated slope during infiltration from rainfall (Vaughan 1985b). In tropical slopes a decrease of permeability with depth can lead to the development of excess pore pressures during infiltration. Such decreases are reported in Hong Kong (GCO 1982), for colluvium overlying residual soil from granite and basalt and, at least over shallow depths, for allophane soils and latosols in Dominica, West Indies, Rouse *et al.* (1986). However, the reverse is reported by Wolle *et al.* (1985), for laterized colluvium overlying residual soil from migmatite.

Where soils are subject to continuous flow from retained water, the possibility of de-flocculating clay–water chemistry should be considered.

6.2.5. Discontinuities of low strength

Such discontinuities often occur and are thought to be relics of discontinuities in the parent rock. The low strength is due to the coating of particles by low-friction iron/manganese organic compounds (St John *et al.* 1969; Koo 1982a; Cowland & Carbray 1988; Irfan & Woods 1988). Angles of shearing resistance on these surfaces may be in the order of $\varphi' = 15\text{–}20°$ when the seams are unsheared, dropping to about $\varphi' = 10°$ when they are pre-sheared and slickensided. Discontinuities may contain smectites (Wolle *et al.* 1985). Pre-shearing may occur due to differential movement during soil genesis. Cadman (1981) discusses the formation of pre-sheared surfaces by the swelling and shrinkage of expansive soils.

Low strength discontinuities are very difficult to discover by boring and drilling. Their influences depend on their continuity, extent and the degree to which they form planar features at critical angles to the stresses imposed by engineering works. This is difficult to determine even when they are exposed in excavation. Koo (1982b) gives a statistical treatment to examine the risk of such discontinuities causing slope failure. They represent a significant and uncertain hazard in the formation of temporary and permanent slopes.

6.2.6. Determination of in situ engineering properties

Because of the probability that in situ inter-particle bonding will be damaged by stress relief and disturbance, the in situ stiffness and strength of a residual soil is likely to be underestimated by both field and laboratory tests.

Reliable settlement characteristics are best determined by relatively large scale loading tests remembering that the effect of soil suctions should be recognized in such tests. They will often be carried out on partially saturated soil in which such soil suctions exist, giving the soil increased strength and stiffness. Thus it is best if field loading tests are conducted on soil in which the water content has been adjusted to the highest value likely in the eventual situation in which the soil is to be loaded.

6.3. Partial saturation

In partly saturated soils both air and water exists in the soil pores. The pressure of the water is always less than that of the air due to the presence of capillary menisci between the two fluids.

The permeability of most residual soils is often high, and they drain quite readily. Water tables are thus often quite low and the supply of underground water limited. If the climate is such that, on average, evapo-transpiration exceeds infiltration, then deep desiccation of the soil profile is likely. This is often the case in warm tropical conditions. The stability of temporary excavations is improved greatly by these conditions. Sometimes average infiltration exceeds evapo-transpiration, and then the net inflow of water maintains relatively high water contents and low pore-water suctions in the soil profile, even though the soil is above the water table and partly saturated.

Two stages of partial saturation can exist. When the soil is relatively dry (degree of saturation typically less than 85%) both air and water influence effective stress and the behaviour of the soil. When the soil has a higher degree of saturation then the air is no longer continuous through the soil but exists in occluded bubbles within the larger pores. This usually occurs when a soil has been flooded with free water and the pore water pressure is equal to or above atmospheric pressure. While the presence of the occluded air affects the undrained compressibility of the soil under load, the pressure of the air in the bubbles has little influence on effective stress, which is controlled by the pore water pressure.

There is often a considerable difference in soil moisture between 'wet' and 'dry' season conditions. This can affect the soil to a significant depth. Thus the time of the year when a soil investigation is performed can affect the results obtained.

Where pore water suctions exist there will be a decrease in effective stress, with a reduction in strength and a tendency to swell if the soil is exposed to free water at zero pressure. For instance, during heavy rain there is a transient loss of strength in slopes of partly saturated soil. When average evapotranspiration exceeds infiltration and there is deep desiccation with large soil suctions, a similar reduction in effective stress is produced if the construction of a building or the sealed pavement of a road prevents evaporation from the ground surface. Thus changes in land usage produce changes in effective stress which may also produce ground movements.

6.3.1. Influence of partial saturation on effective stress

Residual soils frequently exist in the partly saturated state with a continuous air phase in their voids. The pore air pressure will approximate to atmospheric pressure due to the high permeability of the soil to air, but the pore water pressure will be sub-atmospheric due to capillary effects in the small pores of the soil. These pore water suctions give an additional component of effective stress, i.e. effective stresses are greater than total stresses. This increase in strength is not directly proportional to the pore water suction due to the complicating effects of partial saturation but it is an important factor in slope stability. It has been suggested that loss of suction in slopes due to heavy rain is a principal cause of landslides (Wolle *et al.* 1985). However, continuous measurement of pore water suctions in slopes has indicated that, where rainfall is seasonal, suctions are largely removed by rainfall of a duration and intensity which does not cause slope failure (Chipp *et al.* 1982). While a component of strength due to pore water suction may well be relied upon for temporary works, it may be lost in periods of severe rainfall; an important consideration for permanent works.

A simple method of assessing the effect of soil suction is to test the soil drained at its in situ water content (with the soil pores vented to atmospheric pressure) and to compare the strength observed with that for the soil tested drained in its soaked state, i.e. with its pore water pressure elevated to atmospheric pressure (gauge zero).

A more sophisticated (but still practical) way of determining the effect of pore water suction is to express it as apparent cohesion. It has been suggested (Ho & Fredlund 1982) that the apparent cohesion, due to a soil suction varies linearly with the suction i.e. $c_A = (u_a - u_w) \tan \varphi^b$. The value of φ^b can then be determined from multistage triaxial tests in which $(u_a - u_w)$ is varied between stages. Values of φ^b are typically of the order of 20°. Such a value gives an increase in cohesion of 36 kPa for a pore water suction of 100 kPa. Thus even small suctions can have a significant influence on slope stability.

More recently it has been shown that φ_b is a variable which depends on suction, and possibly on other parameters. Escario & Saez (1986) found a bi-linear relationship between shear strength and suction for three soils. Fredlund *et al.* (1987) report a curved envelope for shear strength against suction, with φ_b dropping to 5° for high values of suction. Thus these studies show that there is a limit to the extra strength which can be produced by soil suction. Toll (1988) reviewed available strength data and concluded that this limit depends on clay content.

6.3.2. Partial saturation and collapse

Where soils have been formed under conditions of continuous pore water suction, or where partly saturated soil is elevated to a higher stress in engineering works, the soil can experience a contraction if it is subsequently wetted and the suction reduced or destroyed. This collapse can result from a loss of strength of the individual particles of clusters of particles, or of cementation between particles from loss of strength of 'dry' clay bridges between particles, and from a loss of the stabilizing effects of capillary menisci between particles. Loss of strength of porous particles can occur due to effective stress changes within them, but solid mineral particles can also lose strength when wetted. Collapse can occur in any type of soil, while collapse and heave can occur in the same soil at different stress levels (see Section 6.3.3).

The magnitude of the collapse depends on the extent to which suction is reduced (Maswoswe 1985; Burland 1985). Thus only partial collapse may occur as a result of partial destruction of suction, and further collapse can occur if suctions are reduced subsequently.

Collapse phenomena are common in weathered sands (Jennings & Knight 1957) and may occur in any relatively dry soil. They are best examined by laboratory tests on samples at their natural water content which are wetted under load.

The pre-soaking of dry soil before loading will ameliorate the effects of collapse during subsequent wetting-up (Choudry 1988), although it is likely to give rise to increased settlement under construction loads.

Soaking a soil can cause an increase in pore pressure, a drop in average effective stress and a loss of shear strength. Thus the soaking of highly stressed soil in which suctions exist may cause a shear failure which can be confused with collapse.

6.3.3. Heave

Heave will result from swelling due to a reduction in effective stress (a decrease in total stress or an increase in pore pressure). It may occur in saturated or partly saturated soil.

The amount of heave depends on the magnitude of the effective stress change and on the swelling modulus of the soil $((\delta V/V)/\delta\sigma')$. Swelling modulus increases with the proportion of clay present in the soil and the expansiveness of the clay minerals present. Smectites are usually highly expansive, illites and kaolinites less so. Iron and aluminium oxides, allophanes and halloysites expand little. Heave is generally severe in vertisols ('black cotton soil'). It can also be severe in transported and sedimentary plastic clays. Desiccated soils containing swellable clay minerals heave when subject to a decrease in pore water suction.

Swelling of desiccated plastic clays can cause severe damage to road pavements and to buildings on shallow, lightly-loaded foundations. Damage to lined irrigation canals may be particularly severe.

The risk of heave occurring can be assessed from empirical equations related to soil plasticity, grading, etc. However, such relationships are not well established and are often based on an inadequate range of soils or on tests valid only on a regional basis (Schreiner 1987a, b). Direct swelling tests in the laboratory oedometer apparatus are advisable if the effects of swelling may be critical to the performance of engineering structures. Various types of test are used as discussed in Section 5.5. In general these do not predict the same amount of swell in the same soil. Schreiner (1987c, d) shows that the variation is due to the different stress paths followed in the tests, in particular the development of different horizontal stresses. In general it is advisable to simulate field conditions as closely as possible. A test in which the soil sample is first subjected dry to the stress it will carry in the ground and is then flooded is likely to give the best predictions.

Even if the laboratory test is appropriate, field heave may not be predicted correctly. Typical laboratory tests involve changing the pore water pressure from the field suction (assumed to be that in a sample taken at constant water content) to zero. The eventual pore pressure in the ground may well be less than zero, and the initial suction in the ground may well be different from that in the laboratory sample, depending on the time of year at which the sample was taken, etc.

It is most important to note that heave or collapse can occur in the same soil starting from the same initial conditions, depending on the stress level at which the decrease in effective stress occurs. Thus it is possible for a prediction to be wrong in sign as well as magnitude (El Sohby & Elleboudy 1987).

Heave may be avoided by pre-soaking dry soil, although this may give rise to 'conventional' consolidation settlement under increasing load. It is also possible that shrinkage may be induced if pore pressures are increased by soaking to values higher than ultimate equilibrium values. This is a particular risk in arid areas.

The presence of bonding will inhibit swelling and heave of a bonded soil and swelling may be overestimated if the samples tested have lost bond strength due to disturbance. Similarly, it may be underestimated if destruction of the bonded structure in the field by, say, in situ compaction, is not correctly reproduced.

The magnitude of both heave and collapse is difficult to predict from either laboratory tests or small-scale in situ tests. A near full scale trial at the appropriate stress level is required for accurate prediction.

6.4. Residual soils as fills

When residual soils are excavated and placed as fills their original structure is largely destroyed and they behave in a more 'conventional' manner. However, their original characteristics may still have an effect. The properties of residual soils as fills are reviewed by Cruz *et al.* (1985) and by Nogami *et al.* (1985).

As the sensitive bonded structure of residual soils is destroyed by compaction, the properties of compacted residual soils can be determined with acceptable certainty by conventional soil mechanics tests.

6.4.1. Drained strength and compressibility

Drained strength and compressibility depend on the soil grading, the type of clay minerals present and on the density achieved by compaction. The clay minerals present often result in a higher drained strength than would exist in a sedimentary soil with the same clay fraction.

6.4.2. Permeability and hydraulic properties after compaction

Any macro pores which existed in the original soil will be destroyed by excavation and compaction, and permeability will then reflect mineralogy, grading and density in a conventional manner. The in situ permeability may well be reduced by four orders of magnitude by excavation and compaction as fill.

Soils with kaolinite as the predominant clay mineral have relatively high permeabilities as compared to soils in which smectites are the predominant clay mineral. This reflects the relatively large size of the kaolin particles. Similarly, halloysites and allophanes give relatively high permeabilities. When compacted, these soils may have a compacted permeability in the range 10^{-8} to $5 \times 10^{-10}\,\mathrm{m\,s^{-1}}$.

Permeabilities of this order will allow construction pore pressures to develop in rapidly emplaced fills with high water contents.

6.4.3. Compacted density and water content

Ease of compaction depends on placement water content. Drying prior to or during placement is often not possible in a wet tropical climate except where freedom from rainfall can be relied upon for adequate periods. Some drying during placement is common and inadvertent drying may present a problem if a large increase in water content is required for effective compaction. Wetting may be done best in the borrow pit and at night when evaporation is lowest although an adequate supply of water can be difficult to obtain in the dry season. Drying large amounts of fill is best effected by pre-treatment in the borrow area. The soil should be continuously reworked for maximum effects. Loose soil regains water rapidly if rainfall occurs during treatment.

In some soils high densities may be achieved at water contents well below optimum. Soils compacted in this way may swell or collapse on wetting (Schreiner 1987e). This needs to be considered, using methods as described previously for in situ soils.

6.4.4. Low undrained strength and trafficking problems in fills from residual soils of high void ratio

The in situ water content of a residual soil depends on its void ratio and the degree of saturation, which will be controlled by the local water table and climate. The void ratio may vary widely (Section 6.2.3) and can be very high. If a soil with a high void ratio is below the water table, or even if it is above it in a wet climate where infiltration sustains a high degree of saturation, the water content of a porous residual soil may be very high; then a soil can have a high in situ strength due to its bonded structure, yet may have a very low remoulded undrained strength due to its high water content. In addition it will lose its structural strength as it is re-worked by excavation, placement as fill, compaction and trafficking (Belloni *et al.* 1988). In extreme cases the in situ strength may be that of a weak rock, yet the fully remoulded undrained strength may be of the order of 10 kPa, which is

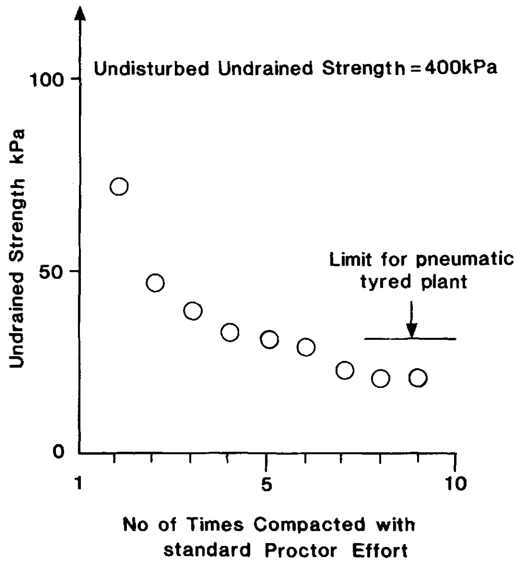


FIG. 6.9. Effect of repeated laboratory compaction on undrained strength of porous residual soil from basalt (Mauritius).

insufficient to support pneumatic-tyred plant. This behaviour is illustrated in Fig. 6.9, which shows the effect of repeated compaction in the laboratory on the undrained strength of a residual soil from basalt from Mauritius. The use of such soils as fill presents great difficulty and special methods of placing and compaction may be needed (Kuno *et al.* 1978; Knight *et al.* 1982). Severe problems also occur in excavation; the soil progressively becoming too weak to support earth-moving plant as it is reworked. Similar problems exist when such soils occur as the sub-base for roads.

These problems can be identified by determining the remoulded undrained strength at the highest water content at which the in situ soil is likely to exist. Degrees of saturation and water contents can vary seasonally to a significant extent and to some depth. It is prudent to determine void ratio as well as water content during a site investigation as this enables the water content to be predicted if the soil becomes wet.

6.4.5. Discontinuities in fills

Discontinuities may be formed in fills of residual soils as in any other fill of cohesive soil. Planar discontinuities may be formed at smooth compaction surfaces, particularly if the surface on which a new layer of fill is placed is dry and dusty. Shear discontinuities may be formed if bearing capacity failure occurs under wheeled plant. The strength of such discontinuities will tend towards the residual strength of the soil. In many residual soils this strength is quite high, and thus discontinuities do not cause significant weakening.

6.4.6. Re-cementation of fills

Some tropical soils show an ability to develop bonds quite quickly by re-cementation after placement. The presence of goethite has been considered to be a potential cause of this (Knill & Best 1970). This may make them brittle and prone to cracking if subject to subsequent deformation.

6.5. Practical difficulties in working with residual soils

Some practical difficulties arise in working residual soils, in addition to those already discussed.

(1) Duricrusts may be sufficiently strong and thick to cause engineering problems, as with penetration of sheet piles, etc.

(2) Core stones, in the transition between residual soil and unweatherd rock, can cause problems in excavations and borrow pits, and also for piling and exploratory drilling.

(3) Problems similar to those of (1) and (2) above may be caused by intrusive veins, dykes and sills which weather differentially—e.g. quartz veins in granite.

(4) Changes in the structure of porous soils during pile driving may result in low pile capacities.

(5) Wet soils rich in iron may adhere to steel plate and stick in the bodies of dump trucks, etc.

(6) Residual soils are often subject to relatively rapid surface erosion when exposed to rainfall and run-off (da Silva *et al.* 1985; Nogami *et al.* 1985).

6.6. Residual soils in road pavements

In most tropical and sub-tropical countries the road network is made up of a mixture of bitumen-surfaced, gravel-surfaced and earth roads. The type of road is usually determined by the volume of traffic. Whereas naturally occurring materials are used for the construction of gravel and earth roads, they are only used in the pavement layers of bitumen surfaced roads when traffic levels are relatively low. For earth roads the natural soil forms the running surface and only minor engineering works are carried out to shape and compact the surface and to improve drainage and stability. Such roads are adequate for 20 or 30 vehicles per day. They are susceptible to changes in moisture conditions and are not expected to be serviceable in the wet season. Expansive clays of the vertisol group are most vulnerable to wet conditions. To ensure all-weather serviceability earth roads need to be improved by surfacing with well graded gravelly soil, usually about 150 mm thick, placed on top of the subgrade. This gravel wearing course should meet specified limits for grading, plasticity and aggregate hardness. Natural gravels of the ferricrete or calcrete variety are widely used when they are locally available and sufficiently hard and durable to resist breakdown under trafficking. The least weathered grades of residual soils may also be suitable for gravel wearing courses.

Specifications for the selection of materials for use in bitumen-surfaced roads (base and sub-base) are generally strictly defined in terms of grading (particle-size distribution), plasticity and strength (California Bearing Ratio) (Transport & Road Research Laboratory 1977). With the exception of some of the better quality duricrust materials (ferricrete, calcrete, etc.) it is unlikely that these requirements will be met by residual soils, except as a sub-base where lower standards are required. However tropical and residual soils may show satisfactory behaviour in road construction even when not meeting specifications derived for temperate conditions (Gidigasu 1988; Hight *et al.* 1988).

When residual soils used in earth roads contain coarse fractions it is important that they are sound and not susceptible to breakdown during compaction or to deterioration during the life of the road. In humid tropical environments, limits have been set for the maximum permissible amount of secondary minerals, as determined by thin section analysis (Weinert 1980). Aggregate tests can be on soaked samples as well as on normal dry samples to ensure that only durable materials are used.

Soils which do not meet the specifications for pavement materials can be improved by stabilization. Mechanical stabilization may be achieved by mixing different materials together but chemical stabilization is more common. With small proportions (of the order of 5% by weight) of portland cement or hydrated lime added to the soil, a tenfold increase in strength may be typical. Alternatively, the plasticity of the soil may be reduced; the response of tropical soils is varied and must be determined by pilot studies. Some residual soils, notably those of volcanic origin, may exhibit pozzolanic properties and react more favourably with cement or lime than other soils. For less plastic or non-plastic soils bitumen stabilization may give better results than chemical stabilization. The cost effectiveness of stabilization must usually be compared with that of processing and hauling conventional road making materials, such as crushed rock.

Residual soils will be encountered in earthworks for roads and special problems arise with fills below pavements. Plastic clays (liquid limit greater than 70%) should be avoided immediately below road surfaces, as volume changes due to wetting or drying are likely to cause cracking which will reach the road surface. Such soils may be treated with lime to reduce plasticity, or replaced with better quality soil. Special care is needed with some soils of the andosol group, which are highly leached and have a loosely cemented structure associated with the presence of iron oxide. If such soils are to be used as fill their collapse potential should be evaluated.

6.7. Duricrusts as sources of aggregate

Duricrust materials and their development are described in Chapter 2. They are potentially valuable sources of aggregate, and an understanding of their formation and distribution will help in the search for the harder materials which may make suitable aggregates. They are likely to vary within a deposit and between deposits, and are unlikely to provide as good a material as crushed rock. It is unlikely that they will be suitable in road surfacings for other than lightly trafficked roads. A further limitation to their use is their susceptibility to polishing. This will apply particularly to ferricretes and calcretes; silcretes will be more resistant.

The normally accepted tests for assessing weaker materials as aggregates should apply, such as the 10% fines test or the modified aggregate impact test. These should be carried out on soaked as well as on dry samples (British Standards Institution 1975b; Collis & Fox 1985; Hosking & Tubey 1969).

Appendix. Field description and practical application

Sections of this Report have indicated procedures that might be adopted in the description, identification and classification of tropical residual soils in the context of trying to appreciate their likely engineering behaviour. This appendix presents a general sequence that may be adapted to suit individual project requirements.

This sequence may be summarized as a logical series of steps.

A. Definition of general environment.
B. Identification of likely soil types.
C. Design and implementation of appropriate investigations.
D. Detailed description of soil/rock profiles.
E. Identification of soil mass/profiles and likely behaviour.
F. Classification of engineering characteristics.

Tables A1 to A4 are included as an aid to the application of this sequence in practice.

The initial step (A) may be aided by the use of checklists such as presented in Tables A1 and A2. By identifying the general site characteristics and by using the definitions in Chapters 2 and 3, and in particular Figure 3.2 in conjunction with Table A2, it should be possible to identify the likely soil/rock types (step B); or at least eliminate impossible options. Table A5 is

TABLE A1. *Preliminary identification: site characteristics location and description*

1. Location			
Position			
Boundaries			
Elevation		Site Extent	
2. Landform			
Relative Relief		Slope Angles	
Profile form		Plan form	
Description			
3. Vegetation			
Vegetation Type		% Cover	
4. Information Sources			
Geology Maps			
Soil Maps			
Key References and Notes			

TABLE A2. *Preliminary identification site characteristics diagnostic features for use with Figure 3.2*

1. Geology				
Bedrock				Parent Material Fig. 3.2
Overburden				
2. Hydrology				
Drainage Pattern				
Water Table: Position		Variation		
Water Table Response to Precipitation				
Soil Drainage impeded?	Yes		No	Drainage Fig. 3.2
3. Current climate				
Rainfall: Annual		Monthly Variation		
Climatic Features				
Climate Grouping				Climate Fig. 3.2
Likely Soil Group				

TABLE A3. *Relative importance of field identification factors*

Property	Field test	Duricrusts M	Duricrusts F	Duricrusts E	Ferrallitic M	Ferrallitic F	Ferrallitic E	Ferrisol & Ferruginous M	Ferrisol & Ferruginous F	Ferrisol & Ferruginous E	Vertisol M	Vertisol F	Vertisol E	Andosol M	Andosol F	Andosol E
Natural properties																
Moisture state	Visual/manual	2	2	2	2	2	2	2	2	2	1	1	2	1	1	1
Colour	Visual	1	1	1	1	1	1	3	3	3	1	1	1	3	3	3
Strength	Manual	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2
	Hand vane	N	N	N	3	2	2	3	2	2	3	2	2	3	2	2
	Penetrometer	N	N	N	3	2	2	3	2	2	3	2	2	3	2	2
	Schmidt hammer	3	1	1	3	1	1	N	N	N	N	N	N	N	N	N
Fabric	Visual	2	1	1	2	1	1	3	2	2	3	2	2	1	1	1
Texture	Visual	1	3	2	1	2	2	2	2	3	2	2	3	2	2	3
	Manual/sieve	1	3	2	1	2	2	2	2	3	2	2	3	2	2	3
Density	Manual	1	2	1	1	2	1	2	2	2	2	3	3	1	1	1
	Relative	2	2	2	2	2	2	2	2	2	2	3	3	1	1	1
Behaviour	Sensitivity	3	3	3	3	3	3	3	2	3	3	2	2	1	1	3
	Durability	2	3	2	2	3	2	3	3	3	3	3	3	3	3	2
	Erosion	3	3	2	3	3	2	2	3	1	3	3	2	3	3	2
	Permeability	3	3	2	3	2	2	3	2	2	3	1	1	3	1	1
	Swell/shrink	3	3	3	3	3	3	2	2	2	1	1	1	1	2	3
	Plasticity	2	3	3	2	3	3	2	2	2	1	1	1	1	2	3
Mineralogy	Visual	1	1	1	1	1	1	1	1	1	2	3	2	2	3	2
	Hardness	2	3	3	2	3	3	2	2	2	2	3	2	2	3	2
Mass properties																
Profile	Log/description	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Structure	Visual	3	3	3	3	3	2	3	1	1	3	3	2	3	3	2
Behaviour	Visual	3	1	1	3	1	1	3	2	1	3	1	1	3	2	1

Main tropical soil groups.

NOTES: M: Soil used as a construction material
F: Soil used as a foundation medium
E: Soil in cutting/excavation

1: Essential soil diagnostic feature
2: Key feature for engineering assessment
3: Not crucial
N: Not relevant

TABLE A4. *Summary of laboratory test applicability for tropical soils*

Property	Laboratory Test	Applicability		
Sensitivity to method of preparation for test	Plasticity	M	F	E
	Shrinkage	M	F	E
	Particle size	M	F	E
Classification	Moisture content	M	F	E
	Plasticity	M	F	E
	Particle density	M	F	E
	Particle size	M	F	E
Density	Bulk density	M		
	Moisture content	M		
Compaction characteristics	Dry density–moisture relationship	M		
	MCV	M		
Strength—undisturbed	Laboratory vane		F	E
	Unconfined compression		F	E
	Triaxial compression		F	E
	Direct shear		F	E
	Residual direct shear			E
Strength—remoulded	Laboratory vane	M		
	Unconfined compression	M		
	Triaxial compression	M		
Compressibility	Oedometer consolidation	M	F	
	Rowe cell consolidation	M	F	
	Triaxial consolidation	M	F	
Swell	Oedometer swell		F	E
Collapse	Oedometer collapse		F	E
Drainage	Laboratory permeability	M	F	E
Erosion	Pinhole test	M	F	E

NOTES: M: Soil used as a construction material
F: Soil used as a foundation medium
E: Soil in cutting/excavation

TABLE A5. *Preliminary identification: typical site*

1. Geology		
Bedrock	Quaternary basaltic and andesitic lavas, breccias and pyroclastics	Parent Material Fig. 3.2
Overburden	Hillwash over residual soil	
2. Hydrology		
Drainage Pattern	Radial	
Water Table: Depth	>3m; Variation:	
Water Table Response to Precipitation	Slight rise	
Soil Drainage Impeded?	Yes: ; No: ✓	Drainage Fig. 3.2
3. Current Climate		
Rainfall: Annual	1750mm; Monthly Variation: 0–300mm	
Climatic Features	Hot, with seasonal heavy rain	
Climate Grouping	Tropical wet	Climate Fig. 3.2
Likely Soil Group	Andosol	

presented as a worked example of such a process, taken from a site in West Java, Indonesia.

The preliminary identification made from steps A and B can then be used to carry out steps C and D more effectively.

Chapter 4 details the characteristics that should be identified in the field when attempting to define a soil material or mass. Although all the listed characteristics (Tables 4.2 and 4.3) should be given attention, it is apparent from Chapters 2 and 3 that there are those with particular significance for some soils. Table A3 is presented as an illustration of the key characteristics over which particular attention must be paid for the main soil groups of Chapters 2 and 3. This table also takes into account the manner in which the soil/rock mass may be affected: by use as a source of material, as a foundation medium, or in excavation.

The design of ground investigations (Table 4.29) and laboratory testing programmes must take into account both the soil/rock types and the use to which it is being put. Table A4 summarizes key laboratory tests that may be undertaken. This table also takes into account the engineering aspects and illustrations of Chapter 6.

It should be remembered in all these steps that a residual soil mass should not be considered in isolation but as a continuum or profile that may include fresh to weathered bedrock and transported material.

Glossary of terms

Accretionary soil. A thick soil formed by simultaneous slow deposition of sediment and pedogenesis often occurring on footslopes where colluvium accumulates.

Activity. The ratio of the plasticity index to the percentage of clay-sized particles (<0.002 mm) in a soil.

Allite. A ferrallitic soil formed in hot, humid tropics in which aluminium oxides predominate.

Allophane. Poorly crystallized alumino-silicate clay formed in fersiallitic soils (andosols) by rapid weathering of volcanic glass.

Alluvium. Unconsolidated sediments deposited by rivers and streams.

Alucrete. Duricrust with >50% aluminium oxide.

Alumina. Aluminium oxide.

Andosol. Porous soils of low bulk density formed by rapid weathering of volcanic ash and containing complexes of humus and imperfectly crystallized aluminosilicate clay (allophane).

Bauxite. Ore of aluminium oxide.

Black cotton soil. Common name for soil which exhibits large volume changes on wetting and drying, caused by the presence of abundant smectite clay minerals.

Calcrete/caliche. Duricrust formed by precipitation of calcium carbonate.

California bearing ratio. The ratio (expressed as a percentage) of the force required to penetrate a circular piston of 1935 mm^2 cross section into the soil from the surface at a constant rate of 1 mm/min, to the force required for similar penetration into a standard sample of crushed rock. The ratio is determined at a penetration of 2.5 mm and 5 mm and the higher value is used.

Catena. Soil sequence influenced by topographical control especially where movement of water and fine particles occurs down a slope.

Cation exchange capacity. The total number of ion exchange sites in a soil, principally on clay and humus particles which can be temporarily occupied by positively charged ions, (Ca, Mg, Na, K, etc.).

Collapse potential. The ratio of the change in volume to the original volume of a soil under a given normal stress when wetted.

Collapsible soil. Soils whose structure can collpase when wetted.

Colluvium. A fine sediment of variable texture formed by run-off and creep on slopes and frequently found on hillslopes where it may overlie a residual soil.

Compaction. The process of packing soil particles closer together by applying mechanical energy.

Consolidation. The process of packing soil particles closer together over a period of time by application of continued pressure. It is accompanied by drainage of water from the voids between solid particles.

Corestones. Residual blocks of hard rock surrounded by soil formed by spheroidal weathering of well jointed igneous rock. Can be up to 10 m diameter. Used to indicate grade of weathering.

Dispersive soil (clays). Clays from which individual colloidal particles readily go into suspension in practically still water.

Dolocrete. A type of duricrust formed by precipitation of carbonates dominated by magnesium.

Drained shear strength. A compression or direct shear test in which full drainage is allowed throughout the test.

Dry density. The mass of material after drying to constant weight at 105°C contained in unit volume of undried material.

Duricrust. Hardened horizons formed in soil profiles by precipitation of various compounds from solution. An example is ferricrete formed by the precipitation of iron oxide.

Effective angle of shear resistance. The slope of the Mohr–Coulomb effective stress envelope, denoted by (ϕ').

Effective cohesion. The intercept of the Mohr–Coulomb effective stress envelope, denoted by c'.

Effective stress (σ'). The difference between the total stress (σ) and the pore pressure (u), i.e. $\sigma' = \sigma - u$.

Effective shear strength parameters. The slope and intercept of the Mohr–Coulomb envelope drawn to a set of Mohr circles of effective stress at failure.

Eluvial. Leached horizon by downward movement of solid particles by percolating groundwater.

Erosion. Removal of soil particles by the movement of water.

Etchsurface. An irregular surface formed by erosion of a deep residual soil mantle to expose much of the underlying basal weathering front of bedrock.

Expansive clay. A clay which swells when it has free access to water if it is not sufficiently restrained.

Ferrallitic soil. Group of soils formed in hot humid tropics principally by hydrolysis of primary minerals, leaving iron and aluminium as residues. Silica, alkalis, hard alkaline earths are removed in solution.

Fersiallitic soil. Formed in sub-tropical or Mediterranean climates where weathering is weaker than in ferruginous soils, and does not affect quartz, alkali feldspars and muscovite. Main clay mineral is smectite but kaolinite may form in well drained areas.

Ferricrete. A duricrust formed by precipitation and accumulation of iron oxide. Texture may vary from pisoliths to massive, blocky or sheet form.

Ferrisoil. Soil type transitional between ferruginous and ferrallitic types.

Ferrite. A ferrallitic soil dominated by iron oxides which occurs mainly on rocks low in aluminium.

Ferruginous soil. Intermediate between fersiallitic and ferallitic soil. Newly formed clays are usually kaolinitic. Some smectite clays persist but lessived gibbsite absent.

Free swell. A test in which a known volume of dried and powdered clay soil is poured into distilled water and the volume of the settled solids is measured.

Goethite. A crystalline hydrated iron oxide formed in soils by residual accumulation of iron in a humid environment or by precipitation from solution.

Gibbsite. A crystalline form of $Al(OH)_3$ which occurs in ferrallitic solids and is the principal constituent of bauxite ore and some rocks.

Gypcrete. A pedogenic, concretionary material rich in gypsum ($CaSO_4.2H_2O$).

Halloysite/metahalloysite. A 1 : 1 clay mineral related to the kaolinite group with hollow tube-shaped crystals. Hydrated halloysite can lose water irreversibly on drying to form metahalloysite.

Haematite. A crystalline iron sesqui-oxide formed by residual accumulation or precipitation from solution in a dry environment.

Illite. A 2 : 1 clay mineral common in sedimentary rocks, siallitic and fersiallitic soils. Characterized by 10 Å X-ray diffraction spacing. The aluminosilicate layers are separated by potassium ions and do not expand and contract with moisture changes.

Illuviation. Downward movement of solid particles (usually clay) through a soil profile by dispersion in percolating groundwater. An upper (eluvial) horizon is consequently depleted in the illuviated material, and a lower (illuvial) horizon is enriched.

Inselberg. Prominent steep-sided isolated hills or mountains rising abruptly from an eroded plain.

Kaolinite. Common 1 : 1 aluminosilicate clay mineral characterized by aluminium silicate layers giving a 7 Å interlayer spacing in X-ray diffraction.

Laterite. A soil material which is impregnated with, cemented by or partly replaced by hydrated oxides of iron or aluminium.

Lateritic. Soil with some tendency to form laterite.

Leaching. Vertical (downward or upward) movement and removal of soluble weathering products from soil horizons. Downward leaching occurs in humid environments, upward in drier areas subject to fairly continuous surface evaporation.

Lessivage. See illuviation.

Linear shrinkage. The amount of shrinkage that occurs in a linear dimension when a soil is dried from its liquid limit to its shrinkage limit.

Linear strain. Change in length per unit length in a given direction.

Montmorillonite. Clay minerals with a three-layer crystal lattice characterized by swelling in water.

Oedometer. Laboratory apparatus in which the one-dimensional consolidation characteristics of a small specimen can be obtained over a range of applied static pressures.

Oxisol. Intensively weathered soil rich in iron and aluminium oxides.

Partial saturation. The condition in which the voids between soil particles are not completely filled with water.

Pedogenesis. Soil formation.

Peneplain. An almost level land surface worn down by prolonged erosion which may be uplifted to form a plateau and then subjected to renewed dissection.

Piping. Movement of soil particles carried by water eroding channels through the soil leading to sudden collapse.

Plinthite. Laterite material containing hydrated oxides of iron and aluminium but with no or only slight evidence of concretionary development. Soft when dug moist, it hardens irreversibly on exposure and desiccation.

Podzol. A soil having a surface layer rich in organic matter overlying a bleached (non-depleted) or allic horizon and then a brown iron-enriched (spodic) horizon.

Pore pressure. Stress in the water filling the voids of a fully saturated soil.

Regolith. The superficial mantle of loose incoherent rock material formed by the sum total of physical and chemical weathering processes and of deposition by water, wind and ice.

Remoulded shear strength. The shear strength of a remoulded soil in an undrained condition.

Residual shear strength. Ultimate shear strength on a rupture plane which a soil maintains at large displacements.

Residual soil. The soil which accumulates in situ by decomposition of rock and leaching of soluble constituents, leaving insoluble materials which are not transported any significant distance. (For fuller description see Chapter 1 of this Report.)

Saprolite. Thoroughly decomposed rock, a clay rich soil formed in place by chemical weathering of igneous or metamorphic rocks; features of original rock structure (e.g. phenocrysts) are often preserved by differences of colour or mineralogy in the clay.

Saturation. The condition in which all the voids of a soil are completely filled with water.

Sensitivity. Ratio between undrained shear strength of undisturbed and remoulded soil.

Shear strain. Change of angle between two planes originally perpendicular to each other.

Shear strength. The shear stress on a failure plane at failure (t_f).

Shear stress. Stress acting tangentially to a given plane.

Shrinkage limit. Maximum water content at which a reduction in water will not cause a decrease in volume of the soil mass.

Silica–sesquioxide ratio. The ratio of silica (SiO_2) to sesquioxides Al_2O_3 and Fe_2O_3 present in a soil. Often used as a crude index of the state of the weathering.

Silcrete. A duricrust formed by the precipitation of silica within the soil profile.

Smectite. Soil clay mineral group containing montmorillonite and other 2:1 minerals composed of aluminosilicate layers with hydroxyl ions between the layers, which consequently expand and contract as the soil wets and dries.

Soil fabric. The three-dimensional arrangement of solid particles and voids in a soil, which is either inherited from the parent material or imposed by pedogenic processes.

Soil texture. A property determined by particle shape and size distribution which determines the feel of a moist sample remoulded between finger and thumb.

Soil suction. Negative pore pressure within a soil.

Specific gravity. The ratio between the mass of the soil particles and the mass of water which they displace.

Spodic horizon. An iron or organic rich subsoil B horizon formed by downward movement of these materials in acidic groundwater.

Stone-line. A line of angular or subangular rock fragments which parallels a sloping ground surface often at a depth of several feet and usually indicates an episode of slope erosion followed by deposition of colluvium.

Stream orders. First-order streams are the small, fingertip streams occurring in the highest parts of a drainage basin. The first-order streams combine to form a second-order stream; two second-order to form a third, etc.

Stress path. A graphical plot of the changes in effective stress which take place within a test specimen or within an element of soil in situ, due to the changes of applied stress.

Swelling. The opposite process to consolidation, i.e. expansion of a clay on reduction of pressure due to water being drawn into the voids between particles.

Swelling pressure. The pressure required to maintain constant volume (i.e. to prevent swelling) when a clay has access to water.

Total stress. The actual stress on a soil mass due to the application of a pressure or force.

Ultisol. Soils less weathered than oxisols, containing kaolinitic clays together with hydrated oxides of iron and aluminium, and broadly equivalent to ferruginous soils and ferrisols.

Unconfined compressive strength. The compressive strength at which failure of a cylindrical specimen occurs when subjected to uniaxial (unconfined) compression.

Vertisols. Soils (cracking clays) showing a wide range of seasonal volume change, and usually containing clay minerals of the montmorillonite group. Clay–humus complexes are often incorporated to some depth by topsoil falling down the cracks, hence the common name of black cotton soil.

Voids ratio. The ratio between the total volume of voids and the total volume of solid particles.

Weathering. The processes of physical breakdown and chemical alteration of rock material in response to contact with air, water and organisms.

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References

ACWORTH, R. I. 1987. The development of crystalline basement aquifers in a tropical environment. *Quarterly Journal of Engineering Geology*, **20**, 265–272.

ADAMS, G. F. (ed) 1975. *Planation surfaces, peneplains, pediplains and etchplains*. Dowden, Hutchinson and Ross, Stroudsburg.

AITCHISON, G. D. 1973. State-of-the-art review of structurally unstable soils. *Proceedings of the 8th International Conference on Soil Mechanics & Foundation Engineering*, Moscow, Vol. 3, 161–190.

ALEVA, G. J. J. 1979. Bauxitic and other duricrusts in Suriname: a review. *Geol. en Mijnbouw*, **58**, 321–336.

ALEXANDER, L. T. & CADY, J. G. 1962. Genesis and hardening of laterite in soils. *Technical Bulletin 1218*, US Department of Agriculture.

ANON. 1975. *A basic system of soil classification for making and interpreting surveys*. Washington: US Department of Agriculture, Soil Conservation Service.

ANON. 1977. The description of rock masses for engineering purposes: Working Party Report. *Quarterly Journal of Engineering Geology*, **10**, 355–388.

ANON. 1979. Classification of rocks and soils for engineering geological mapping. Part 1: Rock and soil materials. (IAEG Commission of engineering geological mapping). *Bull. IAEG.*, **19**, 364–371.

ANON. 1982. Land surface evaluation for engineering practice: Working Party Report. *Quarterly Journal of Engineering Geology*, **15**, 265–316.

BAGUELIN, F., JEZEQUEL, J. F. & SHIELDS, D. H. 1978. *The pressuremeter and foundation engineering*. Trans Tech. Publications.

BAILEY, S. W. 1980. Structures of layer silicates. *In*: BRINDLET, G. W. & BROWN, G. (eds) *Crystal Structures of Clay Minerals and their X-ray Identification*, Mineralogical Society, London 1–123.

BARKSDALE, R. D., BACHUS, R. C. & CLANAN, M. B. 1982. Settlement of a tower on residual soil. *Proceedings of Conference on Engineering & Construction in Tropical Residual Soils, Honolulu*, ASCE 339–356.

——, FERRY, C. T. & LAWRENCE, J. D. 1986. Residual soil settlement from pressuremeter moduli. Use of In-Situ Tests in Geotechnical Engineering, *ASCE Geotechnical Special Publication*, **6**, 447–461.

——, INTRAPRASART, S. & CRIST, R. L. 1975. Settlements of footings on a saprolitic soil. *Proceedings of the 5th Pan-American Conference on Soil Mechanics & Foundation Engineering*, Buenos Aires. **3**,125–134.

BASCOMB, C. L. 1961. A calcimeter for routine use on soil samples. *Chemistry in Industry* 1826–1827.

—— 1964. Rapid method for the determination of cation-exchange capacity of calcareous and non-calcareous soils. *J. Sci. Fd Agric.* **15**, 821–823.

BAYNES, F. J. & DEARMAN, W. R. 1978a. The relationship between the microfabric and the engineering properties of weathered granite. *Bull. IAEG.* **18**, 191–197.

—— & —— 1987b. Scanning electron microscope studies of weatherd rocks: a review of nomenclature and methods. *Bull. IAEG.* **18**, 199–204.

BEAR, FIRMAN E. (ed) 1964. *Chemistry of the soil*. American Chemical Society Monograph No. 160 (2nd edition). Reinhold, New York.

BEAUMONT, T. E. 1979. Remote sensing for the location and mapping of engineering construction materials in developing countries. *Quarterly Journal of Engineering Geology*, **12**, 147–158.

BELLONI, L., MORRIS, D., BELLINGERI, G. A. & PURWOKO, I. 1988. Compaction and strength characteristics of a residual clay from Bali, Indonesia. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*, **1**, 343–50.

BERRY, L. & RUXTON, B. P. 1959. Notes on weathering zones and soils on granitic rocks in two tropical regions. *Journal of Soil Science* **10**, 54–63.

BLEACKLEY, D. 1964. Bauxites and laterites of British Guiana. *Geological Survey of British Guiana Bulletin* **34**.

—— & KHAN, E. J. A. 1963. Observations on the white-sand areas of the Berbic Formation, British Guiana. *Journal of Soil Science* **14**, 44–51.

BLIGHT, G. E. 1982. Residual soils in South Africa, Engineering and Construction in Tropical Soils, *Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference, Honolulu, Hawaii*, 147–171.

—— 1988. Construction in tropical soils. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore.*

BOCQUIER, G. 1973. *Genèse et évolution de deux toposequences de sols tropicaux du Tchad. Interpretation biogeodynamique.* State doctoral thesis, University of Strasbourg.

BOYCE, J. R. 1985. Some observations on the residual strength of tropical soils. *Proceedings 1st International Conference on Geomechanics in Tropical Lateritic & Saprolitic Soils, Brasilia.* **1**, 229–237.

BRACKLEY, I. J. A. 1980. Prediction of soil heave from suction measurements. *Proceedings of the 7th Regional Conference for Africa on Soil Mechanics & Foundation Engineering, Accra, Ghana,* **1**, 235–251.

BRAND, E. W. 1982. Analysis and design in residual soils. *Proceedings, Conference Engineering and Construction in Tropical & Residual Soils, Honolulu.* ASCE. 89–146.

—— 1985. Geotechnical engineering in tropical residual soils. *Proceedings 1st International Conference on Geomechanics in Tropical Lateritic & Saprolitic Soils, Brasilia,* **3**, 23–100.

—— & PHILLIPSON, H. B. 1984. Site investigation and geotechnical engineering practice in Hong Kong. *Geotechnical Engineering,* **15**, 97–153.

—— & —— 1985. Review of international practice for sampling and testing of residual soils. *In*: PHILLIPSON, H. B. (ed). *Sampling & Testing of Residual Soils,* Scorpion Press, Hong Kong. 7–22.

BRESSANI, L. A. & VAUGHAN, P. R. 1989. Damage to soil structure during triaxial testing. *Proceeding of Conference, Rio di Janiero.*

BREWER, R. 1964. *Fabric and mineral analysis of soils.* Wiley, New York.

BRINDLEY, G. W. 1980. Quantitative X-ray mineral analysis of clays. *In*: BRINDLEY, G. W. & BROWN, G., (eds) *X-ray Diffraction Procedures for Clay Mineral Identification*. Mineralogical Society, London, 411–438.

—— & BROWN, G. (eds) 1980. *X-ray Diffraction Procedures for Clay Mineral Identification*. Mineralogical Society, London.

BRINK, A. B. A. *et al.* 1982. *Soil survey for engineering*. Oxford, Clarendon.

—— & KANTEY, B. A. 1961. Collapsible grain structure in residual granite soils in Southern Africa. *Proceedings of the 5th International Conference on Soil Mechanics & Foundation Engineering, Paris*, **1**, 611–614.

BRITISH STANDARDS INSTITUTION, 1975a. *Methods of test for soils for civil engineering purposes*: *BS 1377*: British Standards Institution, London.

BRITISH STANDARDS INSTITUTION, 1975b. *Methods of sampling and testing mineral aggregates, sands and fillers*: *BS 812*. British Standards Institution, London.

BRITISH STANDARDS INSTITUTION. 1981. *Code of Practice for Site Investigations*: *BS 5930*. British Standards Institution, London.

DE BRITTO, A. T. A. 1981. *Chemical and mineralogy study of a weathered profile of migmatic gneiss*. MSc Thesis PUC-RJ, Gavea, RJ, Brazil (in Portuguese).

BUCHANAN, F. 1807. *A journey from Madras through the countries of Mysore, Canara and Malabar*. Vol. 3. London, East India Company.

BULLOCK, P., FEDOROFF, N., JONGERIUS, A., STOOPS, G., TURSINA, T. & BABEL, U. 1985. *Handbook for soil thin section description*. Waine Research Publications, Wolverhampton.

BURLAND, J. B. 1984. Buildings on expansive soils. *Proceedings of the 1st National Conference on Science and Technology of Buildings, Khartoum*. 59–82.

—— 1985. Collapse of partly saturated compacted soil. Discussion, Session 9. *11th International Conference on Soil Mechanics and Foundation Engineering*, San Francisco. **5**, 2842.

BUTT, C. R. M. 1981. Some aspects of geochemical exploration in lateritic terrains in Australia. *In*: *Lateritisation Processes, Proceedings of the International Seminar on Lateritisation Processes, Tivandrum, India, 1979*. Balkema, Rotterdam, 369–380.

CADMAN, J. D. 1981. A morfologia de superfices de auto-rotura em solos expansivos tropicais. Proceedings of the 1st Brazillian Symposium de Solos Tropicais em Engenharia, Rio de Janeiro. **1**, 484–496.

DE CAMPOS, M. T. P. 1980. *Laboratory tests and instrumented surface plate loading tests on a young gneissic residual soil*. MSc Thesis PUC-RJ, Gavea, RJ, Brazil (in Portugese).

CHAN, M. F. 1988. In situ testing of residual soils in Singapore. *Proceedings of the 2nd International Conference on Geomechanics of Tropical Soils, Singapore*, **1**, 97–108.

CHARMAN, J. M. (ed.) 1988. *Laterite in road pavements*. CIRIA Special Publication **47**. London, Construction Industry Research Information Association.

CHAYES, F. 1956. *Petrographic modal analysis*. Wiley, New York.

CHEN, F. M. 1988. *Foundation on expansive soils*. Developments in Geotechnical Engineering 64. Amsterdam, Elsevier.

CHILD, G. H. 1984. Soil description—quo vadis? *In*: HAWKINS, A. B. (ed.) *Site Investigation Practice*: *Assessing BS 5930*. Geological Society, London, Engineering Geology Special Publication **2**, 73–81.

CHIN, F. K. 1988. Construction of dams, roads, airfields and land reclamation in or on tropical soils. *Proceedings of the 2nd International Conference on the Geomechanics of Tropical Soils, Singapore* **2**.

CHIPP, P. N., CLARE, D. G., HENKEL, D. J. & POPE, R. G. 1982. Field measurement of suction in colluvium covered slopes in Hong Kong. *Proceedings 7th South-East Asian Geotechnical Conference, Hong Kong*, **1**, 49–62.

CHOUDRY, T. 1988. Prevention of collapse in residual foundation soils of Guri embankment dams. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*, **1**, 363–368.

CHRISTIAN, C. S. & STEWART, G. A. 1968. Methodology of integrated surveys. *Nat. Resources Res.*, UNESCO 6, 233–280.

CLAYTON, C. R. I., SIMONS, N. E. & MATTHEWS, M. C. 1982. *Site Investigation—A Handbook for Engineers*. Granada Publishing.

COLLINS, K. 1985. Towards characterization of tropical soil microstructure. *1st International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brazilia*, 85–96.

—— & MCGOWAN, A. 1983. Micromorphological studies in soil engineering. *In*: BULLOCK, P. & MURPHY, C. P. (eds) *Soil micromorphology, 1*: *Techniques and Applications*. ABA, 195–218.

COLLIS, L. & FOX, R. A. (eds) 1985. *Aggregates: Sand, gravel & crusted rock aggregates for construction purposes*. Geological Society, London. Engineering Geology Special Publication **1**.

COSTA FILHO, DE M. & VARGAS, E. DO A. and others. 1985. Peculiarities of 'in situ' behaviour of tropical soils—Hydraulic properties. *In*: *Progress Report, Tropical, Lateritic and Saprolitic Soils*. Committee on Tropical Soils, International Society of Soil Mechanics and Foundation Engineering. Brazilian Society for Soil Mechanics. 67–84.

COOK, J. R. & YOUNGER, J. S. 1986. The engineering geology and road projects in North Borneo. *In*: CULSHAW, M. G., BELL, F. G., CRIPPS, J. C. & O'HARA, M. (eds) *Planning and Engineering Geology*. Geological Society, London, Engineering Geology Special Publication **4**, 419–428.

COOK, R. U. & DOORNKAP, J. C., 1974. *Geomorphology in Environmental Management*, Clarendon, Oxford.

COWLAND, J. W. & CARBRAY, A. M. 1988. Three cut slope failures on relict discontinuities in saprolitic soil. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*, **1**, 253–258.

CRAIG, J. R. & VAUGHAN, D. J. 1981. *Ore microscopy and ore petrography*. Wiley, New York.

DA CRUZ, P. T. and others 1985. Peculiarities of Tropical Lateritic and Saprolitic Soils Used as Construction Materials—Dams. *In*: *Progress report, Tropical, Lateritic and Saprolitic Soils*. Committee on Tropical Soils, International Society of Soils Mechanics and Foundation Engineering. Brazilian Society for Soil Mechanics. 67–84.

DEARMAN, W. R., BAYNES, F. J. & IRFAN, T. Y. 1978. Engineering grading of weathered granite. *Engineering Geology*, **12**, 345–374.

—— & TURK, N. 1985. Sampling and testing of residual soils in the United Kingdom. *In*: BRAND, E. W. & PHILLIPSON, H. B. (eds) *Sampling and Testing of Residual Soils,* Scorpion Press, Hong Kong, 175–181.

DEERE, D. U. & PATTON, F. D. 1971. Slope stability in residual soils, *Proceedings of the 4th Pan-American Conference SMFE,* **1,** 87–170.

DIAS, R. D. & GEHLING, W. Y. Y. 1986. Geotechnical aspects of undeformed lateritic soils in south Brazil. *Proceedings of the 5th International Congress IAEG,* Buenos Aires. **2,** 793–797.

DIB, P. S. 1985. Compressibility characteristics of tropical soils making up the foundation of the Tucurui Dam in Amazonia, Brazil. *Proceedings of the 1st International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brasilia.* **2,** 131–142.

DIXON, J. B. & WEED, S. B. 1977. *Minerals in Soil Environments.* Soil Science Society of America, Madison, Wisconsin.

DOWLING, J. W. F. & WILLIAMS, F. H. P. 1964. The use of aerial photographs in material surveys and classification of landforms. *Conference on Civil Engineering Problems Overseas,* ICE, London.

DUCHAUFOUR, P. 1982. *Pedology Pedogensis and Classification* (English Edition Trans. T.R. Paton). George Allen and Unwin, London.

DUDAS, M. J. & HARWARD, M. E. 1975. Weathering and authigenic halloysite in soil developed in Mazama Ash. *Soil Sci. Soc. America Proc.,* **39,** 561–556.

DUMBLETON, M. J. & WEST, G. 1974. Guidance on planning, directing and reporting site investigation. *TRRL Report LR 625.*

DURY, G. H. 1969. Rational descriptive classification of duricrusts. *Earth Science Journal,* **3,** 77–86.

ESTAFF, D. J., BEGGS, C. J. & MCELHENNEY, M. D. 1978. Middle East geotechnical data collection. *Quarterly Journal of Engineering Geology,* **9,** 37–55.

EL SOHBY, M. A. & ELLEBOUDY, A. M. 1987. Swelling and collapsible behaviour of unsaturated cemented sand upon wetting. *Proceedings of the 9th European Conference on Soil Mechanics and Foundation Engineering, Dublin.* **2,** 553–556.

EMERSON, W. W. 1967. A classification of soil aggregates based on their coherence in water. *Australian Journal of Science,* May 1967, p 47.

ESCARIO, V. & SÁEZ, J. 1986. The shear strength of partly saturated soils. *Geotechnique,* **36,** 453–456.

FAIRBRIDGE, R. W. & FINKL, C. W. Jr. 1984. Tropical stone lines and podzolised sand plains as palaeoclimatic indicators for weathered cratons. *Quaternary Science Review,* **3,** 41–72.

FANIRAN, A. 1974. The extent, profile and significance of deep weathering in Nigeria. *Journal of Tropical Geography,* **38,** 19–30.

FEININGER, T. 1971. Chemical weathering and glacial erosion of crystalline rocks and the origin of till. *In*: *Geological Survey Research 1971, US Geological Survey Professional Paper,* 750C C65–C81.

FERREIRA, H. N. 1985. Characterization, identification and classification of tropical lateritic and saprolitic soils for geotechnical purposes. *Proceedings of the 1st International Conference on Tropical Soils,* Brazil.

FITZPATRICK, E. A. 1983. *Soils, Their Formation, Classification and Description.* Longman.

FOLSTER, H., MOSHREFI, N. & OJENUGA, A. G. 1971. Ferralitic pedogenesis on metamorphic rocks, SW Nigeria. *Pedologie, Ghent,* **21,** 95–124.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 1985. *Soil map of the world 1:5 000 000 revised legend.* F.A.O., Rome.

FOSS, I. 1973. Red soil from Kenya as a foundation material. *Proceedings of the 8th International Conference on Mechanics and Foundation Engineering,* Moscow, **2,** 73–80.

FREDLUND, D. G. & ROHARDJO, H. 1985. Theoretical context for understanding unsaturated residual soil. *Proceedings of the 1st International Conference on Geomechanics of Tropical Soils, Brasilia,* **1,** 295–306.

——, —— & GAN, J. K. M. 1987. Non-linearity of strength envelope for unsaturated soils. *Proceedings of the 6th International Conference on Expansive Soils,* New Delhi, **1,** 49–54.

FROST, R. J. 1976. Importance of correct pretesting preparation of some tropical soils. *Proceedings of the 1st S-E Asian Conference on Soil Engineering,* Bangkok.

GASKIN, A. R. C. 1975. Investigation of the residual iron ores of Tonkilili District, Sierra Leone. *Transactions of the Institute of Min. Metal., Sec. B. Applied Earth Science,* B98–B119.

GERRARD, A. G. 1988. *Rocks and landforms.* Unwin Hyman, London.

GEOTECHNICAL CONTROL OFFICE, Hong Kong 1982. *Mid-Levels, Study, Report on geology, hydrology and soil properties.*

—— 1987. *Geoguide 2: Guide to site investigation.*

—— 1988. *Geoguide 3: Guide to rock and soil descriptions.*

GHOSH, K. P. & DUTTA, B. C. 1978. Mineralogy and genesis of Phut Kapahar bauxite deposits of Eastern Madha Pradesh, India. *4th International Congress for the Study of Bauxite, Alumina and Aluminium (ACSOBA),* **1,** 204–225.

GIBBS, H. J. & HOLTZ, W. G. 1956. Engineering properties of expansive clays. *Trans. ASCE,* **121,** 1, Paper 2814.

GIDIGASU, M. D. 1972. Mode of formation and geotechnical characteristics of laterite materials of Ghana in relation to soil forming factors. *Engineering Geology,* **6** 79–150.

—— 1976. *Laterite soil engineering. Developments in geotechnical engineering,* **9.** Elsevier Amsterdam.

—— 1988. The use of non-traditional tropical and residual materials for pavement construction—a review. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore.* **1,** 397–404.

—— & ANDOH, M. B. 1980. Broad regional evaluation of expansive soil conditions. *Proceedings of the 7th Regional Conference for Africa on Soil Mechancis and Foundation Engineering, Accra, Ghana,* **1,** 235–251.

GILLMAN, G. P. 1979. A proposed method for the measurement of exchange properties in highly weathered soils. *Australian Journal of Soil Research* **17,** 129–139.

GIPSON, M. Jr. 1963. Ultrasonic disaggregation of clays. *J. Sedimentary Petrology,* **33,** 955–958.

GRADWELL, M. W. & BIRRELL, K. S. 1954. Physical properties of certain volcanic clays. *New Zealand Journal Science and Technology.* **B36,** 37–48.

GRIFFIN, O. G. 1954. *A New Internal Standard for the Quantitative X-ray Analysis of Shales and Mine Dust.*

Research Report No. 101, Safety in Mines Research Establishment. Ministry of Fuel and Power.

GRIM, R. E. 1968. *Clay mineralogy*. McGraw Hill, New York.

GRUNDY, P. J. & JONES, G. A. 1976. *The structures and properties of solids 7: Electron microscopy in the study of materials*. Edward Arnold, London.

GOUDIE, A. S. 1973. *Duricrusts in Tropical and Sub-tropical Landscapes*. Clarendon, Oxford.

—— & PYE, K. (eds) 1983. *Chemical Sediments and Geomorphology*. Academic, London.

HAANTJENS, H. A. & BLEEKER, P. 1970. Tropical weathering in the Territory of Papua New Guinea. *Australian Journal of Soil Research*, **8**, 157–177.

HEAD, K. H. 1980. *Manual of Soil Laboratory Testing*, Volume 1. Pentech, London.

—— 1982. *Manual of Soil Laboratory Testing*, Volume 2. Pentech, London.

—— 1986. *Manual of Soil Laboratory Testing*, Volume 3. Pentech, London.

HEYLIGERS, P. C. 1963. Vegetation and soil of a white-sand savanna in Surinam. *Verhand. Kon. Ned. Akad. Wetenschappen, Natuurkunde, Tweede Reeks, Deel Liv.*, **3**.

HIGHT, D. W., TOLL, D. G. & GRACE, H. 1988. Naturally occurring gravels for road construction. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*, **1**, 405–12.

HO, D. Y. F. & FREDLUND, D. G. 1982. Increase in strength due to suction for two Hong Kong soils. *Proceedings Conference Engineering and Construction in Tropical and Residual Soils, Honolulu*. ASCE. 263–295.

HODGSON, N. 1973. *Soil Survey Handbook*. Soils Survey of England and Wales, Rothamsted.

HORN, A. 1982. Swell and creep properties of an African black clay. Engineering and Construction in Tropical Soils, *Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference*, Honolulu, Hawaii, 172–198.

HOSKING, J. R. & TUBEY, L. W. 1969. *Research on low grade and unsound aggregates*. Report LR 293, Transport and Road Research Laboratory, Crowthorne, Berks.

HOWATT, M. D. 1988. The in situ strength of saturated decomposed granite. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*, **1**, 311–316.

—— & CATER, R. W. 1982. Passive strength of completely weathered granite. *1st International Conference on Tropical, Lateritic and Saprolitic Soils, Brasilia*. **2**, 371–379.

International Manual for the Sampling of Soft Cohesive Soils 1981. Tokai University Press, Tokyo.

INTERNATIONAL SOCIETY OF ROCK MECHANICS (ISRM). *Rock Characterisation, Testing and Monitoring: Suggested Methods*. ed. E. T. Brown, Pergamon.

INTERNATIONAL SOCIETY OF SOIL MECHANICS AND FOUNDATION ENGINEERING, 1985. Geomechanics in tropical lateritic and saprolitic soils. *Proceedings of the 1st International Conference, Brasilia, February 1985.*

—— 1987. *Expansive soils 6th International Conference, December 1987.* Dehli, Central Board of Irrigation and Power.

IRFAN, T. Y. 1988. Fabric variability and index testing of a granite saprolite. *Proceedings of the 2nd Conference on Geomechanics in Tropical Soils, Singapore*, 25–37.

—— & WOODS, N. W. 1988. The influence of relict discontinuities on slope stability in saprolitic soils. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*, 267–277.

JASMUND, K. 1979. X-ray fluorescence spectroscopy. *In*: VAN OLPHEN, H. & FRIPIAT, J. J. (eds). *Data handbook for clay materials and other non-metallic minerals.* Pergamon, London, 155–161.

JENKINS, R. & DE VRIES, J. L. *An introduction to X-ray powder diffractometry*. Messrs Pye Unicain Ltd., York Street, Cambridge, CB1 2PX.

JENNINGS, J. E., BRINK, A. B. A. & WILLIAMS, A. A. B. 1973. Revised guide to soil profiling for civil engineering purposes in Southern Africa. *The Civil Engineer in South Africa*, January 3–12.

—— & KNIGHT, K. 1957a. The prediction of total heave from the double oedometer test. *Symposium on Expansive Clays, S.A. Inst. Civ. Eng.*, South Africa.

—— & ——. 1957b. The additional settlement of foundations due to collapse of structure of sandy subsoil on wetting. *Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering*, London. **1**, 316–319.

JOINT COMMITTEE FOR THE POWDER DIFFRACTION STANDARDS. 1974. *Selected Powder Diffraction Data for Minerals*. J.C.P.D.S., Pennsylvania, USA.

KALEMBASA, S. J. & JENKINSON, D. S. 1973. A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. *J. Sci. Fd. Agric.* **24**, 1085–1090.

KLUG, H. P. & ALEXANDER, L. E. 1974. *X-ray Diffraction Procedures for Polycrystalline and Amorphous Material.* New York.

KNIGHT, D. J., WORNER, N. M. & MCLUNG, J. E. 1982. Materials and construction methods for a very wet clay core rockfill dam at Monasavu, Fiji. *Transactions 14th International Congress Large Dams, Rio de Janiero*, **4**, 293–304.

KNILL, J. L. & BEST, R. 1970. Mineralogical, chemical and geotechnical studies of core materials in the Kainji and Shek Pik Dams. *Proceedings of the 1st International Conference Engineering Geology*, 1247–1257.

KOIZUMI, T. & ITO, K. 1963. Compressibility of certain volcanic clays. *Soils and Foundations*, **3**, No. 2, 37–48.

KOMOO, I. & MOGANO, S. N. 1988. Physical characterisation of the weathering profile of clastic metasediments in Peninsular Malaysia. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*, 37–43.

KOO, Y. C. 1982a. Relic joints in completely decomposed volcanics in Hong Kong. *Canadian Geotechnical Journal*, **19**, 117–123.

—— 1982b. The mass strength of jointed residual soils. *Canadian Geotechnical Journal*, **19**, 225–231.

KUNO, G., SHINOKI, R., KONDO, T. & TSUCHIYA, C. 1978. On the construction methods of a motorway embankment on a sensitive volcanic clay. *Proceedings Conference Clay Fills*, Institution of Civil Engineers, London. 149–156.

LACERDAR, W. A., SANDRONI, S. S., COLLINS, K., DIAS, R. D. & PRUZZA, Z. V. 1985. Compressibility properties of lateric and saprolitic soils. *In*: *Progress Report 1982–5 on*

Tropical Lateritic and Saprolitic Soils, Brazilian Society for Soil Mechanics, 85–114.

LAMBE, T. W. & WHITMAN, R. V. 1969. *Soil Mechanics*. Wiley, New York, 318–321.

LEE, I., WHITE, W. & INGLES, O. 1978. *Geotechnical Engineering*, Pitman.

LAWRANCE, C. J. & TOOLE, T. 1984. The location, selection and use of calcrete for bituminous road construction in Botswana. *TRRL Laboratory Report LR 1122*. Crowthorne: Transport and Road Research Laboratory.

LELONG, F. 1969. Nature et genese des produits d'alteration de roches crystallines sous climat tropical humide. *Memoire Science de la Terre, Nancy*, 1–14.

LEMME, C. R. DE M. and others 1985. Peculiarities of 'in situ' behaviour of tropical soils—Dam foundations. *In*: Progress Report, Tropical, Lateritic and Saprolitic Soils. Committee on Tropical Soils, International Society of Soil Mechanics and Foundation Engineering. Brazilian Society for Soil Mechanics. 239–271.

LEROUEIL, S. & VAUGHAN, P. R. 1990. The general and congruent effects of structure in natural soils and weak rocks.

LOHNES, R. A. & DEMIREL, T. 1973. Strength and structure of laterites and lateritic soils. *Engineering Geology*, **7**, 13–33.

LOMBARDI, G. 1980. *For better thermal analysis*. International Confederation for Thermal Analysis, University of Rome, Italy.

LUM, W. B. 1982. Engineering problems in tropical and residual soils in Hawaii. Engineering and Construction in Tropical Soils, *Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference*, Honolulu, Hawaii, 1–12.

LUM, P. 1962. The properties of decomposed granite. *Geotechnique*, **12**, 226–243.

——. 1965. The residual soils of Hong Kong. *Geotechnique*, **15**, 180–194.

LUTTON, R. J. 1977. Design and construction of compacted shale embankments. Vol 3: Slaking indexes for design. *US Army Engineers Waterways Experimental Station, Vicksburg*. Report No. FNWA-RD-77-1. 80pp.

LUPINI, J. F., SKINNER, A. E. & VAUGHAN, P. R. 1981. The drained residual strength of cohesive soils. *Geotechnique*, **31**, 181–213.

MABBUTT, J. A. 1961. 'Basal surface' or 'weathering front'. *Proceedings of the Geological Association*, **72**, 357–359.

—— 1965. The weathered landsurface in Central Australia. *Z. Geomorphol.*, NF9, 82–114.

MCFARLANE, M. J. 1976. *Laterite and Landscape*. Academic, London.

—— 1983. Laterites. *In*: GOUDIE, A. S. & PYE, K. (eds) *Chemical Sediments and Geomorphology*. Academic, London.

MCHARDY, W. J. & BIRNIE, A. C. 1987. Scanning electron microscopy. *In*: WILSON, M. J. (ed) *A handbook of determinative methods in clay mineralogy*. Blackie, Glasgow.

MACKENZIE, R. C. 1970. *Differential thermal analysis* **1** *Fundamental aspects*. Academic, London.

—— 1980. Differential thermal analysis and differential scanning calorimetry; similarities and difference. *Anal. Proc.* **17**, 217–220.

—— 1984. Origin and development of differential thermal analysis. *Thermochim. Acta*, **73**, 307–367.

MAIGNIEN, R. 1966. Review of research on Laterites. *Natural Resources Research*, **4**. UNESCO, Paris.

MALAMO, S. 1986. Penetration resistance and basic engineering properties of laterite profile soils. *Proceedings of the 5th International Congress of the International Association of Engineering Geology, Buenos Aires*. **2**, 821–828.

MARDIA, K., KENT, J. T. & BIBBY, J. M. 1979. *Multivariate analysis*. Academic, London.

MARTIN, R. E. 1977. Estimating foundation settlement in residual soils. *Journal of Geotechnical Engineering Division ASCE*, **GT3**, 197–212.

MARTIN, R. P. 1986. Use of index tests for engineering assessment of weathered rocks. *Proceedings of the 5th International Congress of the International Association of Engineering Geology, Buenos Aires*. **1**, 433–450.

MASSEY, D. 1988. Stability of slopes and excavations in tropical soils. General Report. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*.

MASSEY, J. B. & PANG, P. L. R. 1899. Stability of slopes and excavations in tropical soils. *Proceedings of the 2nd International Conference on Geomechanics of Tropical Soils, Singapore*. **2**.

MASWOSWE, J. 1985. Stress paths for a compacted soil during collapse due to wetting. *PhD Thesis*, University of London.

MEDINA, J. & LIU, B. S. 1982. The influence of a collapsible foundation on the design of Guri embankment dams. Transactions of the 14th International Congress on Large Dams, Rio de Janeiro. **2**, 241–260.

DE MELLO, V. F. B. 1972. Thoughts on soil engineering applicable to residual soils. *Proceedings of the 3rd South-East Asia Conference on Soil Engineering*, Hong Kong, 5–34.

——. 1980. Comparative behaviour of similar compacted earth-rock dams in basalt geology, Brazil. *Proceedings of Symposium Problems and Practice of Dam Engineering*, Bangkok. Balkema, 61–79.

DE MELLO, L. G. F. S., FRANCO FILHO, J. M. M. & ALVISE, C. R. 1988. Grouting of caniculae in residual soils and behaviour of the foundations of Balbina Dam. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore*. **1**, 385–90.

MILLOT, G. 1984. *Geologie des argiles*. Masson, Paris.

MILNE, G. 1935. Some suggested units of classification and mapping, particularly for East African soils. *Soil Research* (I.S.S.S), **4**, 183–198.

MITCHELL, C. W. 1973. *Terrain Evaluation*. Longman.

MITCHELL, J. K. & SITAR, N. 1982. Engineering properties of tropical residual soils. *Proceedings of the ASCE Conference Engineering and Construction in Tropical and Residual Soils*, 30–57.

MOH, Z. C. & MAZHER, F. M. 1969. Effects of method of preparation on index properties of lateritic soils. *7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City*. **1**, 23–25.

MOORMAN, F. R. 1981. Representative toposequences of soils in southern Nigeria, and their pedology. *In*: GREENLAND, D. J. (ed.) *Characterisation of Soils in Relation to their Classification and Management for Crop Production: Examples from some Areas of the Humid Tropics*, 10–29.

MORGENSTERN, N. & MATOS, M. M. DE 1975. Stability of slopes in residual soils. *Proceedings of the 5th Pan-American Conference Soil Mechanics and Foundation Engineering, Buenos Aires*. **3,** 367–383.

MORI, H. 1982. Site investigation and soil sampling for tropical soils. Engineering and Construction in Tropical Soils, *Proceedings of the ASCE Geotechnical Engineering Division Special Conference, Honolulu, Hawaii,* 58–88.

—— 1985. Sampling and testing of granitic residual soils in Japan. *In*: BRAND, E. W. & PHILLIPSON, H. B. (eds) *Sampling and Testing of Residual Soils,* Scorpion Press, Hong Kong, 99–108.

MORIN, W. J. 1982. Characteristics of tropical red residual soils. Engineering and Construction in Tropical Soils, *Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference, Honolulu, Hawaii,* 172–198.

—— & TUDOR, P. C. 1975. Laterite and lateritic soils and other problem soils of the tropics. *In*: *Engineering Evaluation and Highway Design Study* AID. 3682. Lyon Associates Inc., Baltimore, Md, USA.

MUN, K. P. 1985. Sampling and testing residual soils in Malaysia. *In*: BRAND, E. W. & PHILLIPSON, H. B. (eds) *Sampling and Testing of Residual Soils,* Scorpion Press, Hong Kong, 109–120.

MURPHY, C. P. 1986. *Thin section preparation of soils and sediments*. AB Academic Publishers, Berkhamstead.

NESSE, W. D. 1986. *Introduction to Optical Mineralogy*. Oxford University Press, New York, 325.

NETTERBERG, F. 1971. Calcrete in road construction. CSIR Research Report 286, *National Institute for Road Research* Bulletin, **10**.

—— 1980. Geology of Southern African calcretes: I. Terminology, description and classification. *Transactions Geological Society of South Africa,* **83,** 255–283.

—— 1985. Pedocretes. *In*: BRINK, A. B. A. (ed), *Engineering Geology of Southern Africa* Volume 4. *Post-Gondwana deposits*. 286–207. Building Publications, Silverton.

NEWILL, D. 1961. A laboratory investigation of two red clays from Kenya. *Geotechnique,* **11,** 302–318.

NICHOLLS, G. D. 1962. A scheme for recalculating the chemical analyses of argillaceous rocks for comparative purposes. *Am. Miner.,* **47,** 34–46.

NOGAMI, J. S. and others 1985. Peculiarities of Tropical Lateritic and Saprolitic Soils Used as Construction Materials—Roads. *In*: *Progress Report, Tropical, Lateritic and Saprolitic Soils*. Committee on Tropical Soils, International Society of Soil Mechanics and Foundation Engineering. Brazilian Society for Soil Mechanics. 67–84.

NORRISH, K. & CHAPPELL, B. W. 1967. X-ray fluorescence spectrography. *In*: ZUSMAN, J. (ed.). *Physical methods in determinative mineralogy*. Academic, London.

OLLIER, C. D. 1975. *Weathering* (2nd Edn.). Longman, Edinburgh.

—— 1976. Catenas in different climates. *In*: DERBYSHIRE, E. (ed.). *Geomorphology and Climate*. Wiley, London, 137–169.

PAGE, A. L., MILLER, R. H. & KEENEY, D. R. 1982. *Methods of Soil Analysis Part 2. Chemical and Microbiological Properties*. American Society of Agronomy and Soil Science Society of America, Madison.

PAQUET, H. 1969. *Evolution geochimique des mineraux argileux dans les alterations et les sols des climats mediterranees et tropicaux*. State doctoral thesis, University of Strasbourg.

PARRISH, W. & MACK, M. 1963. *Charts for the solution of Bragg's Equations. Vol. 1–3.* Philips Technical Library Centre, Eindhoven, The Netherlands.

PARTRIDGE, T. C. & MAUD, R. R. 1987. Geomorphic evolution of Southern Africa since the Mesozoic. *South African Journal of Geology,* **90,** 179–208.

PATERSON, E. 1981. The value of differential scanning calorimetry in assessing the physical and chemical properties of particle surfaces. *In*: DOLLIMORE, D. (ed.) *Proceedings of the Second European Symposium on Thermal Analysis* Heyden and Son, London, xxii–xxx.

—— & SWAFFIELD, R. 1987. Thermal analysis. *In*: WILSON, M. J. (ed.) *A handbook of determinative methods in clay mineralogy*.

PAVLAKIS, M. 1980. Pressuremeter testing of weathered Karroo siltstone. *Proceedings of the 7th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Accra,* **1,** 147–158.

PEDRO, G. 1984. La genese de argiles pedologiques, ses implications mineralogiques, physico-chimiques et hydriques. *Sci. Geol. Bull.,* **37,** 333–347.

PHILLIPSON, H. B. & CHIPP, P. N. 1982. Air foam sampling of residual soils in Hong Kong. *Proceedings of the Conference Engineering and Construction in Tropical and Residual Soils, Honolulu*. ASCE, 339–356.

—— & BRAND, E. W. 1985. Sampling and testing residual soils in Hong Kong. *In*: BRAND, E. W. & PHILIPSON, H. B. (eds) *Sampling and Testing of Residual Soils,* Scorpion Press, Hong Kong.

PITTS, J., BROMS, B. B. & KANNAN, R. 1985. The choice of design parameters from '*in situ*' tests in residual soils in Singapore. *Proceedings of the 1st International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils,* Brasilia. **2,** 101–110.

PRESCOTT, J. A. & PENDLETON, R. L. 1952. Laterite and lateritic soils. *Tech. Comm., Commonwealth Bur. Soil Sci.,* **47**.

PRUDEN, G. & KING, H. G. C. 1969. A scheme of semi-micro analysis for the major elements in clay minerals, based on modifications to conventional methods of silicate analysis. *Clay Minerals,* **8,** 1–13.

PRUSZA, Z., KLEINER, D. E. & SUNDERAM, A. V. 1983. Design construction and performance of large dams on residual soil. *Proceedings of the 7th Panamerican Conference Soil Mechanics and Foundation Engineering, Vancouver,* **1,** 169–183.

——, DE FRIES, K. & SCHMIDT, R. 1983. The compressibility of undisturbed and compacted residual soils at Guri. *Proceedings of the 7th Panamerican Conference Soil Mechanics and Foundation Engineering, Vancouver,* **1,** 185–198.

RADWAN, A. M. 1988. Properties of granitic soil in Aswan, Egypt. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils, Singapore,* **1,** 203–210.

RAMSAY, D. M., DHIR, R. K. & SPENCE, J. M. 1977. Practical and theoretical merit of AIV in the study of crushed rock aggregates. *Proceedings of the Conference on Rock Engineering, Newcastle, UK*.

REDFERN, J. P. 1970. Complementary methods. *In*:

MACKENZIE, R. C. (ed.) *Differential thermal analysis*, **1**, 123–158.

RHOADES, J. D. 1982. Cation exchange capacity. *In*: A. L. PAGE, R. H. MILLER & D. R. KEENEY (Eds) *Methods of Soil Analysis Part 2. Chemical and microbiological properties.* American Society of Agronomy and Soil Science Society of America, Madison, 149–157.

RICHARDS, B. G. 1985. Geotechnical aspects of residual soils in Australia. *In*: BRAND, E. W. & PHILLIPSON, H. B. (eds), *Sampling and Testing of Residual Soils*, Scorpion Press, Hong Kong. 23–30.

ROCHA, R. & CELSO, P. 1983. Residual soil elastic properties from in situ tests. *Proc. Symposium In-Situ Testing, Paris*, **2**, 119–123.

ROCHA-FILHO, P. & CARVALHO, J. B. Q. DE. 1988. Building foundations in tropical, lateritic and saprolitic soils. *Proceedings of the 2nd International Conference on Geomechanics of Tropical Soils, Singapore*, **2**.

ROUSE, W. C., READING, A. J. & WALSH, R. P. D. 1986. Volcanic soil properties in Dominica, West Indies. *Engineering Geology*, **23**, 1–28.

ROWE, P. W. 1972. The relevance of soil fabric to site investigation. *Geotechnique*, **22**, 193–300.

RUDDOCK, E. C. 1967. Residual soils of the Kumasi District in Ghana. *Geotechnique*, **17**, 359–377.

RUXTON, B. P. & BERRY, L. 1957. Weathering of granite and associated erosional features in Hong Kong. *Geological Society of America Bulletin*, **68**, 1263–1292.

—— & —— 1961. Weathering profiles and geomorphic position on granite in two tropical regions. *Revue de Geomorphologie Dynamique*, **12**, 16–31.

ST JOHN, B. J., SOWERS, G. F. & WEAVER, CH. E. 1969. Slickensides in residual soils and their engineering significance. *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City*. **2**, 591–597.

SAMESHIMA, T. & BLACK, P. M. 1979. Clay Index—A simple method of assessing the quality and performance of road aggregates. *Proceedings of the New Zealand Road Symposium*, 1979. National Roads Board, Wellington, New Zealand.

SANDRONI, S. S. 1981. Solos residuais pesquisas realizadas na PUC-RJ. *Proceedings of the Brazilian Symposium Engineering of Tropical Soils*, RJ. **2**, 30–65.

—— 1985a. Discussion stress relief effects in gneissic saprolitic soils. *Proceedings of the 1st International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brasilia*. **3**, 290–296.

—— 1985b. Sampling and testing of residual soils in Brazil. *In*: BRAND, E. W. & PHILLIPSON, H. B. (eds). *Sampling and Testing of Residual Soils*, Scorpion Press, Hong Kong, 31–50.

—— & MACCARINI, M. 1981. Triaxial and direct shear tests on a young residual soil from gneiss. *Proceedings Brazilian Symposium Engineering of Tropical Soils*, RJ, **1**, 324–339.

SCHACHTSCHABEL, P. VEN, 1971. Methodenvergleich zur H—Bestimming ven Boden. *PflErnahr. Dung, Bodenk.* **130**, 37–43.

SCHELLMANN, W. 1981. Considerations on the definition and classification of laterites. *In*: *Lateritisation Processes, Proc. Internat. Seminar on Lateritisation Processes*, Trivandrum, India, 1979, Balkema, Rotterdam, 1–10.

SCHMERTMANN, J. H. 1969. Swell sensitivity. *Geotechnique*, **19**, No. 4, 530–533.

SCHREINER, H. D. 1987a. The use of predictive methods in expansive soil engineering. *Proceedings of the 9th African Conference on Soil Mechanics and Foundation Engineering, Lagos*, **1**, 135–142.

—— 1987b. State-of-the-art review of expansive soils. Transport and Road Research Laboratory, Crowthorne, Berks.

—— 1987c. Stress paths during swelling of compacted soils under controlled suction. *Proceedings of the 6th International Conference on Expansive Soils, New Delhi.* **1**, 155–160.

—— 1987d. Discussion. Stress-paths during swelling. *Proceedings of the 9th European Conference on Soil Mechanics and Foundation Engineering, Dublin.* **3**, 1159.

—— 1987e. Swelling of soils compacted dry of the plastic limit. *Proceedings of the 6th International Conference on Expansive Soils, New Delhi.* **1**, 395–398.

SCHULTZ, L. Q. 1964. Quantitative Interpretation of Mineralogical Composition from X-ray and Chemical Data for the Pierre Shale. *US Geological Survey Prof. Paper 391-e.*

SHERARD, J. L., DUNNIGAN, L. P. & DECKER, R. S. 1976. Identification and nature of dispersive soils. *J. Geo. Eng. Div., ASCE*, Paper 12052.

——, ——, —— & STEELE, E. F. 1976. Pinhole test for identifying dispersive soils. *J. Geo. Eng. Div., ASCE*, Paper 11846.

——, RYKER, N. L. & DECKER, R. S. 1972. Piping in earth dams of dispersive clay. *Proceedings of the ASCE Speciality Conference on the performance of earth and earth-supported structures*, **1**.

SILVA, R. F. DA and others 1985. Peculiarities of 'in situ' behaviour of tropical soils—Erosion. *In*: *Progress report, Tropical, Lateritic and Saprolitic Soils.* Committee on Tropical Soils, International Society of Soil Mechanics & Foundation Engineering. Brazilian Society for Soil Mechanics. 117–163.

SINGH, R. B. & AL-LAYLA, M. T. 1980. Engineering behaviour and microstructures of a collapsible Mosul clay under physico-chemical reversal of leaching. *Proceedings of the 6th Southeast Asian Conference on Soil Engineering, Taipei*, 127–137.

SIVARAJASINGHAM, S., ALEXANDER, L. T., CADY, J. G. & CLINE, M. G. 1962. Laterite. *Advances in Agronomy*, **14**, 1–60.

SMART, P. & TOVEY, N. K. 1981. *Electron microscopy of soils and sediments: examples.* Clarendon, Oxford.

—— & —— 1983. *Electron microscopy of soils and sediments; techniques.* Clarendon, Oxford.

SMITH, D. A. M. 1985. A material characterisation of laterised pallid zone soils, near Worsley, Western Australia. *Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco*, **2**, 663–667.

SOIL SURVEY STAFF 1975. *Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys.* US Department of Agriculture Handbook 436, US Government Printing Office, Washington DC.

SOWERS, G. F. 1963. Engineering properties of residual soils derived from igneous and metamorphic rocks. *Proceedings of the 2nd Panamerican Conference Soil Mechanics and Foundation Engineering, Brazil.* **1**, 39–62.

SPEIGHT, J. G. 1967. Lands of Bougainville and Baku Islands, Territory of Papua and New Guinea. Appendix 1: Explanation of land system descriptions. Land Research Series No. 20 *Commonwealth Scientific and Industrial Research Organisation*, Australia.

SRIDHARAN, A., RAO, S. M. & MURTHY, N. S. 1986. Liquid limit of montmorillonite soils. *Geotechnical Testing Journal,* ASTM **9,** 156–159.

STANDARDS ASSOCIATION OF AUSTRALIA, 1980. AS 1289, C8.1-1980. *Determination of the Emerson Class Number of a soil.*

STRAHLER, A. N. 1970. *Introduction to Physical Geography.* 2nd Edn, Wiley.

STRAKHOV, N. M. 1967. *The Principles of Lithogenesis* (Vol. 1), Oliver and Boyd, Edinburgh.

SUMMERFIELD, M. A. 1983. Silcrete. *In*: GOUDIE, A. S. & PYE, K. (eds) *Chemical Sediments and Geomorphology.* Academic Press, London, 59–91.

SWEENEY, D. J. & HO, C. S. 1982. Deep foundation design using plate-load tests. *Proceedings of the 7th Southeast Asian Geotechnical Conference, Hong Kong.* **1,** 439–452.

TAN, B. K. 1986. Use of the standard penetration test for ground interpretations—some examples from peninsular Malaysia. *Proceedings of the 5th International Congress of the International Association of Engineering Geology,* Buenos Aires. **2,** 839–848.

TAYLOR, R. K. 1985. Cation exchange in clays and mudrocks by methylene blue. *J. Chem. Tech. Biotechnol.,* **35A,** 195–207.

TERZAGHI, K. 1958. Design and performance of Sasamua Dam. *Proceedings Institution Civil Engineers,* London. **9,** 369–394.

THOMAS, M. F. 1969. Geomorphology and land classification in tropical Africa. *In*: THOMAS, M. F. & WHITTINGTON, G. A. (eds) *Environment and Land Use in Africa,* Methuen, 103–145.

—— 1974. *Tropical Geomorphology.* Macmillan, London.

—— 1986. Savanna. *In*: FOOKES, P. G. & VAUGHAN, P. R. (eds) *A Handbook of Engineering Geomorphology.* Surrey University Press, 125–136.

THOREZ, J. 1976. *Practical Identification of Clay Minerals* ed. LETLOTTE, G., Dison, Belgium.

TOLL, D. G. 1988. *The behaviour of unsaturated compacted naturally-occurring gravel.* PhD Thesis, University of London.

TRANSPORT & ROAD RESEARCH LABORATORY 1977. A guide to the structural design of bitumen-surfaced roads in tropical and sub-tropical countries. Department of Transport, Transport & Road Research Laboratory, Crowthorne. Road Note 31.

TRESCASES, J. J., MELFI, A. J. & D'OLIVERA, S. M. B. 1981. Nickeliferous laterites of Brazil. *Laterisation Processes, Proceedings of International Seminar on Lateritisation Processes, Tivandrum, India, 1979.* 170–184.

TUNCER, E. R., LOHNES, R. A. & DEMIREL, T. 1977. Desiccation of soils derived from volcanic ash. *Transportation Research Record,* **642,** National Academy of Sciences, Washington D.C., 44–49.

TWIDALE, C. R. & HUTTON, J. T. 1986. Silcrete as a climatic indicator: discussion. *Palaeogeography, Palaeoclimatology Palaeoecology,* **52,** 351–360.

UEHARA, G. 1982. Soil science for the tropics. *Proceedings of the ASCE Conference, Engineering and Construction in Tropical and Residual Soils.*

VALETON, I. 1983. Palaeoenvironment of lateritic bauxites with vertical and lateral differentiation. *In*: WILSON, R. C. L. (ed.) *Residual Deposits: Surface Related Weathering Processes and Materials.* Geological Society London, Special Publication **11,** 77–90.

VAN DER MERWE, D. H. 1964. The weathering of some basic igneous rocks and their engineering properties. *The Civil Engineer in South Africa,* 213–222.

VAN OLPHEN, H. & FRIPIAT, J. J. (eds) 1979. *Data handbook for clay materials and other non-metallic minerals.* Pergamon, Oxford.

VARGAS, M. 1953. Some engineering properties of residual clay soils occurring in southern Brazil. *Proceedings of the 3rd International Conference Soil Mechanics and Foundation Engineering, Zurich.* **1,** 67–71.

—— 1973. Structurally unstable soils in Southern Brazil. *Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow,* **2,** 239–246.

—— 1974. Engineering properties of residual soils from the south-central region of Brazil. *Proceedings of the 2nd International Conference of International Association of Engineering Geology, Sao Paulo, Brazil,* **1.**

—— 1979. Settlements of footings, mat or raft foundations. *Proceedings of the 6th Pan-American Conference on Soil Mechanics and Foundation Engineering, Lima.* **2,** 333–340.

—— 1982. The use of the Atterberg limits in the classification of tropical soils. *Proceedings of the 7th Brazilian Conference on Soil Mechanics and Foundation Engineering,* **5.**

—— 1983. A Brazilian experience in construction and maintenance of roads on tropical rainy mountainsides. *Proceedings of the 7th Pan-American Conference on Soil Mechanics and Foundation Engineering, Vancouver.* **1,** 259–268.

—— 1985. The concept of tropical soils. *Proceedings of the 1st International Conference on Tropical Soils, Brazil.*

—— 1988. Characterisation, identification and classification of tropical soils. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils,* Singapore, 71–77.

VAUGHAN, P. R. 1985. Mechanical and hydraulic properties of in situ residual soils. General Report, Session 2. *Proceedings of the 1st International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brasilia.* **3,** 231–263.

—— 1988. Characterizing the mechanical properties of *in situ* residual soil. *Proceedings of the 2nd International Conference on Geomechanics Tropical Soils, Singapore,* **2.**

—— & KWAN, C. W. 1984. Weathering, structure and in situ stress in residual soil. *Geotechnique,* **34,** 43–59.

——, MACCARINI, M. & MOKHTAR, S. M. 1988. Indexing the engineering properties of residual soil. *Quarterly Journal of Engineering Geology,* London, **21,** 69–84.

WALLACE, K. B. 1973. Structural behaviour of residual soils of the continually wet Highlands of Papua New Guinea. *Geotechnique,* **23,** No. 2, 203–218.

WEINERT, H. H. 1974. A climatic index of weathering and its application in road construction. *Geotechnique,* **24(4)** 475–488.

—— 1980. *The natural road construction materials of Southern Africa.* Pretoria: H & H Academica.

WELTMAN, A. J. & HEAD, J. M. 1983, *Site Investigation Manual. CIRIA Spec. Pub.* No. 25.

WESLEY, L. D. 1973. Some basic engineering properties of halloysite and allophane clays in Java, Indonesia. *Geotechnique,* **23,** 471–494.

—— 1977. Shear strength properties of halloysite and allophane clays in Java, Indonesia. *Geotechnique,* **27,** 125–136.

—— & MATUSCHKA, T. 1988. Geotechnical engineering in volcanic ash soils. *Proceedings of the 2nd International Conference Geomechanics in Tropical Soils, Singapore.* **1,** 333–342.

WILLIAMS, A. A. B. 1980. Severe heaving of a block of flats near Kimberley. *Proceedings of the 7th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Accra, Ghana,* **1,** 301–309.

WILLNER, J. L., FUTRELL, G. E. & LANGFELDER, J. 1982. Settlement predictions in Piedmont residual soil. *Proceedings of Conference on Engineering and Construction in Tropical and Residual Soils, Honolulu. ASCE,* 629–646.

WOLLE, C. M. and others 1985. Peculiarities of 'in situ' behaviour of tropical soils—Slope stability. *In*: *Progress Report, Tropical, Lateritic & Saprolitic Soils.* Committee on Tropical Soils, International Society of Soil Mechanics and Foundation Engineering. Brazilian Society for Soil Mechanics, 165–221.

WOPFNER, H. 1978. Silcretes in northern South Australia and adjacent regions. *In*: LANGFORD-SMITH, T. (ed.) *Silcrete in Australia.* University of New England, Department of Geography, Armidale.

WRIGHT, R. L. 1963. Deep weathering and erosion surfaces in the Daley River Basin, Northern Territory. *Journal of the Geological Society of Australia,* **10,** 151–163.

YOUNG, A. 1976. *Tropical Soils and Soil Survey.* Cambridge University Press.