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Notes

Shear strength of soils derived from the weathering of granite and gneiss in Brazil

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Abstract: Research on the properties of residual soils has been continuing in Brazil since the pioneering work by Vargas in 1953. A great number of earth dams built since then and the initiation of graduate courses since 1960 have increased the rate of in-depth studies on this theme. This contribution considers the more recent research on the properties of these soils, mainly shear strength parameters.

The classification and main properties of tropical residual soils, such as their compressibility, permeability and shear strength, have been treated extensively in the near past (Vargas 1953, 1974, 1985; Sandroni 1977, 1981, 1991; Bell 1981; Carvalho *et al.* 1985; Lacerda *et al.* 1985; Nogami *et al.* 1985; Lacerda & Almeida 1995; Fookes 1997; Futai *et al.* 2004, 2006). The 1985 International Conference on the theme remains the key reference of the subject (Anonymous 1985). The microstructures of these soils have also been studied to a certain degree (e.g. Sandroni 1977; Collins 1985). Saturated colluvial slopes in tropical regions have been reported by Lacerda (2004), who showed that these slopes have a natural angle about half the residual friction angle of these materials. The initiation of slides in saprolites and colluvium has been reported by Lacerda (2007). The present contribution will focus on the more recent advances in the research of microstructure and shear strength of these soils.

Weathering profiles

A large part of Brazil is composed of rocks dating from the Precambrian, mainly granites and gneisses (Fig. 1). This 'shield' encompasses the southern and southeastern regions, which include mountain ranges up to 2000 m in height and in which there are many major cities. Basalt lava flows occupy a large part of the mid-western and southern regions. The weathering of these rocks is thus of great concern regarding the problem of stability of slopes, as these rocks are subjected to a tropical climate, with rainfall reaching a total of 2000 mm or more each year.

The weathering profile of residual soils in Brazil proposed by Vargas (1974) shows the sequence of residual soil layers derived from granites, gneisses and basalts. He called 'mature residual soil' what is now known as lateritic soil and 'young residual soil' the saprolitic soil. The terms lateritic soil and saprolitic soil were adopted during the International Conference on Tropical Soils (Anonymous 1985). Pastore (1995) proposed the weathering profile shown in Table 1.

The term saprolite 'refers to that part of the weathering profile where the soil largely preserves the microfabric and volume of the parent rock' (Aydin 2006). Saprolitic soil is saprolite with more advanced weathering, but that has not undergone the process of laterization. The uppermost section of the saprolitic soil is considered as 'mature', or lateritic soil, as a result of the process of laterization. The weathering profile in a tropical region very often shows a very narrow or indistinct V horizon.

Figure 2 shows a typical residual soil profile of a gneissic rock. The superficial, reddish layer is lateritic, and the light yellow layer is saprolitic. In the saprolitic soil and in the saprolite horizon relict structures of the original rock are visible. Figure 3 shows a saprolite horizon of banded gneiss, showing mica-rich planes involved in a slide. The slickenside of this failure plane is shown in Figure 4. The role of these field-scale heterogeneities in the stability of slopes was studied by Aydin (2006).

In Figure 5 a well-drained residual soil profile of gneiss is shown with some geotechnical parameters. The B horizon (with a thickness of about 3 m) comprises the lateritic soil, which has a porous structure and therefore a high void ratio ($e = 1.5$), and a high clay content (about 50%), contrasting with the lower clay content of the saprolitic soil below, with a void ratio less than unity. The predominant clay mineral in the saprolitic soil is kaolin. The phreatic level is 8 m below the ground surface, and the natural water content lies between the plastic and liquid limits.

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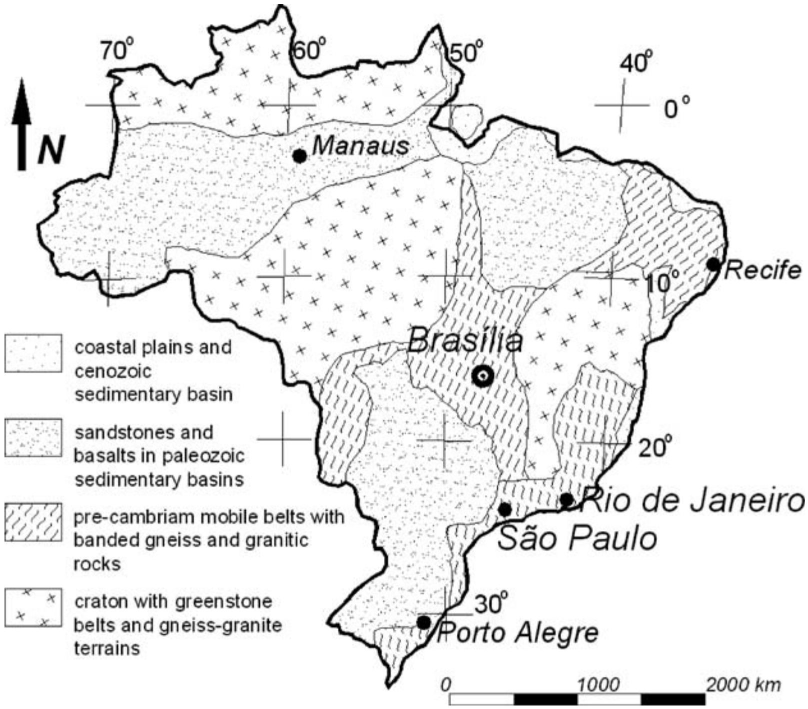


Fig. 1. Simplified geological map of Brazil (after Pires 1998).

Laterites, lateritic and saprolitic soils

Laterites and lateritic soils form a group comprising a wide variety of red, brown, and saprolitic soils that are the result of deep weathering of the parent rock that has not yet undergone laterization. The soil name 'laterite' was coined by Buchanan (1807) in India, from the Latin word 'later' meaning brick. Such soils are characterized by forming hard, impenetrable and often irreversible pans when dried. They are found at shallow depths, in low-grade slopes, and are so tough that they are used in Brazil as concrete aggregate, construction stone for pavements and rip-rap for the protection of dam slopes from the wave action of reservoirs. Figure 6 shows a typical laterite. The rounded forms of the oxides enveloping the grain structure should be noted. These 'stones' are widely used in the northern regions of Brazil, in which rock outcrops are rare, as construction material, and even as concrete aggregate.

Laterites may vary from a loose material to a massive rock. Because of this confusion, most workers now prefer to use definitions based on hardening, such as 'ferric' for iron-rich cemented crusts, 'alcrete' or bauxite for aluminum-rich cemented crusts, 'calcrete' for calcium carbonate-rich crusts, and 'silcrete' for silica-rich cemented crusts (Fookes 1997). Other definitions are based on the ratios of silica (SiO_2) to sesquioxides (Fe_2O_3, Al_2O_3). This has the index k_r. In 'true' laterites the k_r values, are less than 1.33. Those between 1.33 and 2.0 are indicative of lateritic soils, and those greater than 2.0 are indicative of non-lateritic soils (Gidigasu 1976). Bell (1981) gave a comprehensive review on the general characteristics and genesis of laterites and lateritic soil.

Table 1. *Weathering profile according to Pastore (1995)*

Residual or transported soil	I, organic horizon II, lateritic soil horizon
Residual soil	III, saprolitic soil horizon
Transition from soil to rock	IV, saprolite horizon
Rock mass	V, highly weathered rock horizon VI, weathered rock horizon VII, sound rock

Other mineralogical indices

Rocha Filho *et al.* (1985) reviewed many mineralogical indices such as X_d, N_q and N_{qo} (Lumb 1962), and concluded

Fig. 2. A 40 m high cut exposing lateritic (red) and saprolitic (light yellow) soils from gneiss, in Rio de Janeiro State. The weathered rock layer is below the group of people in the centre of the photograph.

that mineralogical weathering indices based upon the content of unstable reference minerals are of limited use, mainly because of the difficulty in their determination. Those workers found that 'referential minerals should be chosen as a function of rock type and climate, and should be used to evaluate the degree of decomposition along the same profile'. Jenny (1941) introduced the 'degree of lixiviation', β, defined as

$$\beta = ba_1(\text{weathered rock})/ba_1(\text{sound rock}) \quad (1)$$

where

$$ba_1 = (K_2O + Na_2O)/Al_2O_3. \quad (2)$$

Fig. 3. Gneiss saprolite, showing relict planar structures of the sliding surfaces rich in mica at right, in shadow.

Fig. 4. Slickensides in the planar layer of mica-rich saprolitic soil.

Bernardes *et al.* (1992) have shown that in a residual soil of leptinitic gneiss β increases with depth, from 0.1 to unity, which reflects a gradual weathering of the parent rock, as seen in Figure 7. They also found that the only parameter affected by β was the effective cohesion intercept for flooded direct shear specimens.

Sandroni (1977) studied gneissic residual soils, and found that the mineralogy of the sand fraction, including the proportions of mica and feldspar, correlates well with the strength of the soil, which tends to be higher as the feldspar content increases and the mica content decreases. Figure 8 shows how the mineralogy of the coarse fraction affects the shear strength of saprolitic gneissic soil.

Structure of saprolitic and lateritic soils

Soils are classified according to grain size: clay, silt, sand, gravel, etc. The mineralogy of each fraction deserves special attention, and generally a description is made of the various clay minerals, as well as of the sand and silt particles (quartz, carbonate, feldspar, etc.). A transported and sedimented soil has a structure in which the grain sizes are sorted during the depositional process, and this is sufficient for their characterization.

However, a simple description in terms of mineralogy and grain size does not suffice when the subject is residual soil. Residual soil has an inherited structure from the parent rock, and also a structure resulting from pedogenetic processes. Saprolitic soils are derived from saprolites, an advanced state of weathered rock. As these soils undergo further weathering the clay content increases, and by exposure to lixiviation plus oxidation of iron and aluminum ions such soils are transformed to lateritic soils. An advanced state of lateritic soils is laterite. Lateritic soils are erosion-resistant, whereas saprolitic soils are not. In short, saprolitic soils are formed in the transition from weathered rock to completely weathered rock, and their clay fraction is small, usually less than 10%, as can be seen in Figure 5. Lateritic soils have a larger clay fraction, up to 60%, but this clay fraction is aggregated with oxides, forming links with the larger grain sizes.

Collins (1985) stated that 'it is clear that a wide variety of microstructural forms and levels of fabric organization will exist in lateritic and saprolitic soils. Complex multi-level pore systems will be found, involving unequal pore sizes'. In our opinion each geotechnical application (stability of natural slopes, compacted soils, pavements, foundations, etc.) should use the most appropriate description of the soil for the purpose in view, including its genesis, climate and so on, and include mechanical tests so as to obtain data that are comparable with those for other soils.

Some attempts have been made in recent decades to find simple methods to characterize residual soils, employing laboratory tests.

Nogami & Villibor (1981) and Nogami *et al.* (1989) made an interesting proposal for the classification of

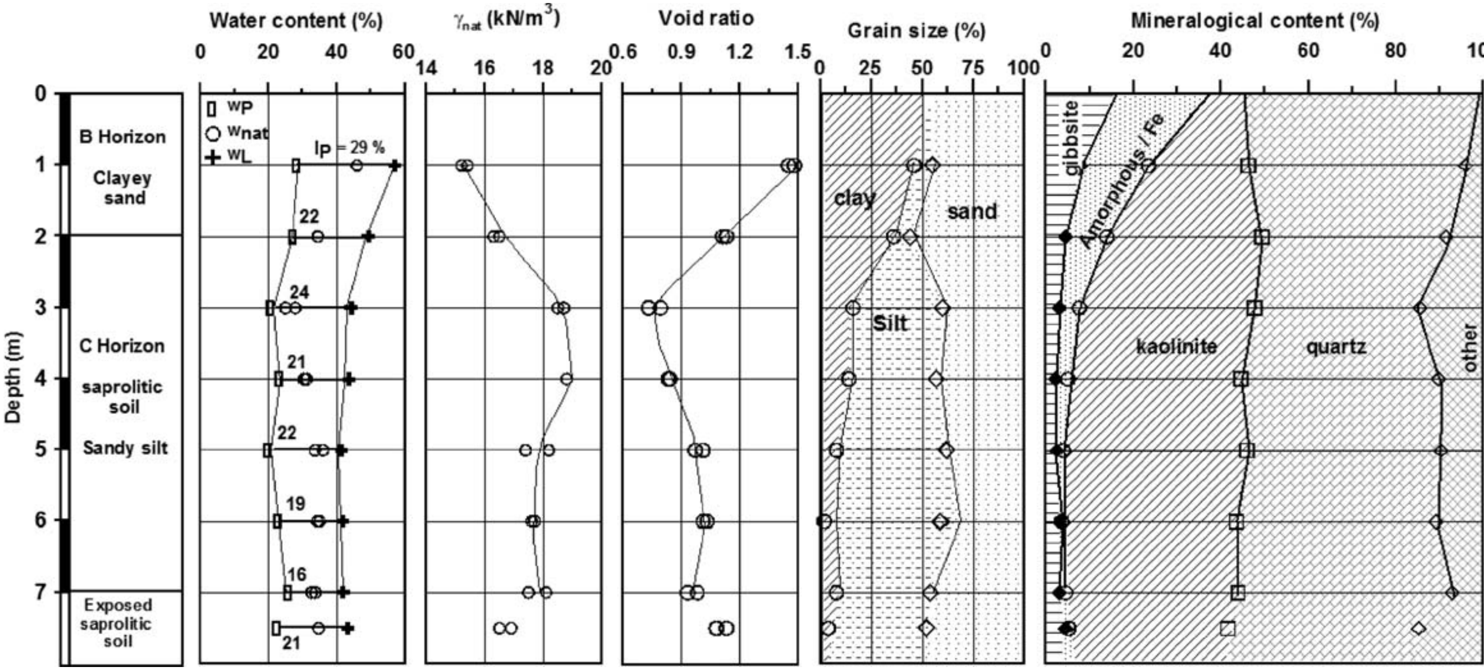


Fig. 5. Profile of the residual gneissic soil at Ouro Preto, Minas Gerais, Brazil (Futai *et al.* 2004).

Fig. 6. Laterite from Goiás State, Brazil.

residual soils, using mechanical compaction tests (mini-MCV, 'moisture condition value') to distinguish soils with a lateritic and non-lateritic behaviour. This proposal started out as an answer to problems encountered in pavement design in tropical regions, where some lateritic soils, by the usual classification systems used in road design, where soil structure is completely destroyed, were rejected as unacceptable, mainly on grounds of undesirable swelling characteristics. Nevertheless, they behaved extremely well in roads that were not 'designed' according to the then prevailing standards. Also in pavement research, De Medina (1989) suggested the use of resilient moduli to differentiate the behaviour of lateritic soil and saprolitic soils.

Lateritic and saprolitic soils show the presence of macro- and micro-pores the size and distribution of which can be investigated by means of the mercury intrusion technique. Futai *et al.* (2004) have performed such tests in a typical tropical soil, whose profile and characterization data can be seen in Figure 5. This is a typical residual soil from gneiss in the State of Minas Gerais, near Ouro Preto, Brazil (Futai *et al.* 2004). Pore-size distribution (PSD) was investigated by Futai *et al.* (2004) means of scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP). These studies were performed on oven-dried specimens. SEM studies for the soil at 1 m and 5 m depth are shown in Figure 9. The particles of the soil at 1 m depth (Fig. 9a) appear to be aggregated and large pores may be observed, although the clay minerals are not clearly observed. SEM for the soil at 5 m depth (Fig. 9b) showed voids and large parallel plates of kaolin. Porosimetry measurements obtained by Futai *et al.* (2004) using MIP are shown in Figure 10, for incremental intrusion. The soil at 1 m depth showed a clear bimodal distribution of pores, with macro-pores in the range 10–100 μm and micro-pores smaller than 0.1 μm. The soil at 5 m depth had only macro-pores larger than 2 μm, but concentrated in the ranges 2–10 μm and 30–300 μm. Porosimetry measurements appear to confirm the results of the grain-size analysis; that is, horizon B possesses smaller pores and higher clay content than horizon C. The overall analysis of grain size, soil microscopy and porosimetry suggests a metastable structure for the horizon B soil comprising micro- and macro-pores.

The soil water retention curve for this soil reflects the pore-size distribution. The bimodal retention curve for the soil at 1 m depth is typical of tropical highly weathered soils (Carvalho & Leroueil 2000) containing aggregated particles that are uncemented or cemented by iron oxides linked by clay bridges. According to the same researches, these soils have two air entry points, corresponding to macro- and micro-pores. The soil at 5 m depth has a retention curve with two slopes but no plateau, which appears to be consistent with the two ranges of macro-pores at 2–10 and 30–300 μm (Fig. 11).

Porosimetry measurements appear to confirm the results of the grain-size analysis; that is, horizon B possesses smaller pores and higher clay content than horizon C. The

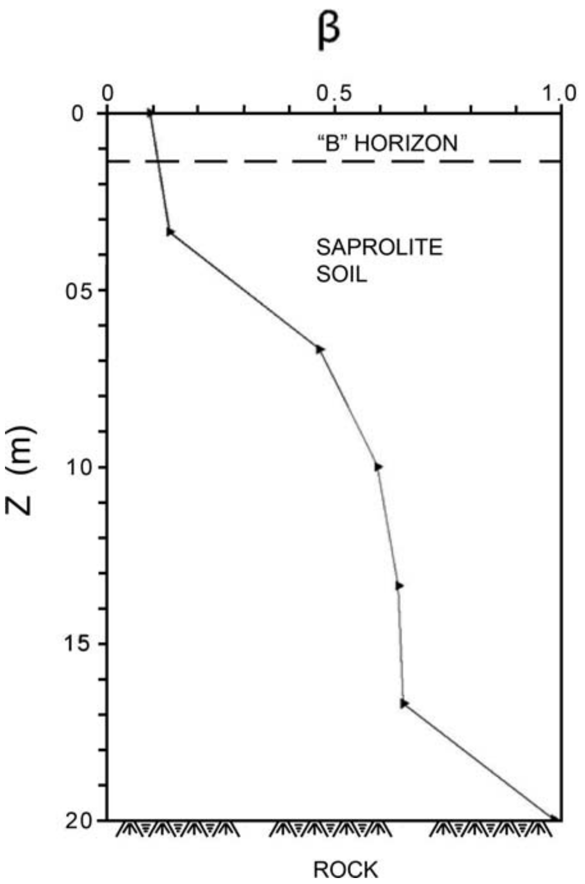


Fig. 7. The beta index v. depth in a gneiss residual soil profile in Rio de Janeiro (Adapted from Bernardes *et al.* 1992).

overall analysis of grain size, soil microscopy and porosimetry suggests a metastable structure for the horizon B soil comprising micro- and macro-pores.

Identification of lateritic soils

For a rapid assessment of whether a soil is lateritic or not the immersion technique (slaking test, or crumb test) can be used. Lateritic soils remain intact even 24 h after immersion, because of their true effective cohesion, whereas saprolitic soils crumble rapidly. Of course, soils in the initial state of laterization may also crumble, but not as completely and as rapidly as a saprolitic soil. Therefore this test is not fail-proof, and the determination of the k_r index is necessary.

Another way to distinguish these soils is by means of the Soil Conservation Service (SCS) double hydrometer test (Decker & Dunningan 1976). The SCS test was originally aimed at identifying dispersive soils, but can be used to distinguish soils with lateritic and non-lateritic behaviour. The clay content of a lateritic soil determined by a grain-size analysis without any dispersing agent and low mechanical action is practically zero, because the aggregates are not destroyed (Fig. 12). If the analysis is made with mechanical agitation and dispersing agent, the clay particles are loosened from the aggregates and clay contents as high as 60% (or higher) are measured.

In situ void ratios

The natural void ratio varies according to the type of parent rock and degree of weathering. Table 2 shows the range of void ratios found by several researchers in Brazil. It can be seen that there is an increase in void ratio from saprolitic soil to lateritic soil. However, there are instances where the colluvial layer may exhibit an *in situ* void ratio of the same order as that of the underlying residual soil, depending on the genesis of the colluvial layer. If the colluvium is formed by a translational or rotational slide of the residual soil, it may preserve the characteristics of the residual soil. If the colluvium was weathered by laterization after complete destructuring of the residual soil, it will exhibit larger void ratios. It may, therefore, be collapsible or not at low vertical stresses, depending on the degree of laterization.

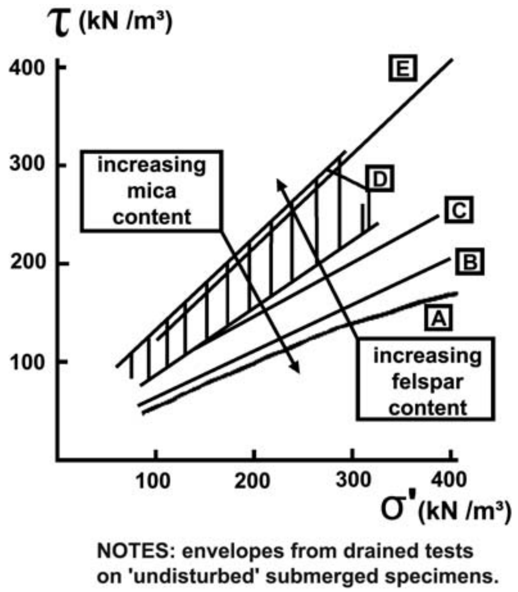
Shear strength of tropical soils

Some work has been done on this subject. Sandroni (1977, 1991), Maccarini (1988) and Massey *et al.* (1989) called attention to the influence of mineralogy on the shear strength parameters of a saprolitic soil from gneiss, as shown in Figure 8.

The Mohr envelope of shear strength tests is generally curved (Fig. 13). The curved portion is due to structure effects. The test results given in the present study were all obtained in saturated conditions. Gan & Fredlund (1996) also found an initial curved Mohr envelope for two saprolitic soils of Hong Kong, as can be seen in Figure 14. Suction has a great influence on the Mohr envelope, shifting it upwards, as shown by Fredlund & Rahardjo (1993). The influence of suction is to increase the cohesion intercept, with an insignificant influence of the effective friction angle.

The existence of true cohesion

Cohesion is found in rocks, and is lost in the weathering process. Effective cohesion in soils is usually zero. However, true effective cohesion can occur in saturated cemented soils. The oxides of lateritic soils form a weak cement, and true cohesion, although small, exists. This cohesion is not



AUTHOR SITE	GRAIN SIZE (%)			VOIDS RATIO	STRENGTH ENVELOPE	COARSE GRAINS MINERALS
	SAND	SILT	CLAY			
CAMPOS (1974) CATINGUEIRO	92	5	3	.76	CURVED A	Q: 30-60 F: – 0 M: 40-70
VARGAS (1951) VILA ANASTÁCIO	40	44	16	1.0	CURVED B	High mica Content Some felspat
SERAPHIM (1974) ESTRADA DE FURNAS	75	19	6	.95	c'=40 kN /m³ ø' = 29.5° C	Q: 48-60 F: 11– 23 M: 22-28
SANDRONI (1973) RIO	50 to 80	15 to 30	5 to 25	.30 to .90	c'=17 to 35 kN /m³ D ø' = 34 to 43°	Low mica content
SERAPHIM (1974) ESTRADA DE FURNAS	83	13	4	.70	c'=25 kN /m³ ø' = 43° E	Q: 48-58 F: 30– 42 M: 6-14

NOTE: Q: quartz F: feldspar M: mica

Fig. 8. Relationship between the mineralogy and the shear strength parameters of residual soils from gneiss in Rio de Janeiro (Sandroni 1977).

lost in a saturated state. Saturated saprolitic soils do not show this effective cohesion, whereas saturated lateritic soils do. However, the determination of this true cohesion poses a challenge in laboratory tests. Standard triaxial tests require that the minimum principal stress be greater than zero, or equal to zero, in the case of the unconfined compression test. The determination of this cohesion is difficult, even using direct shear tests, because of the low confining

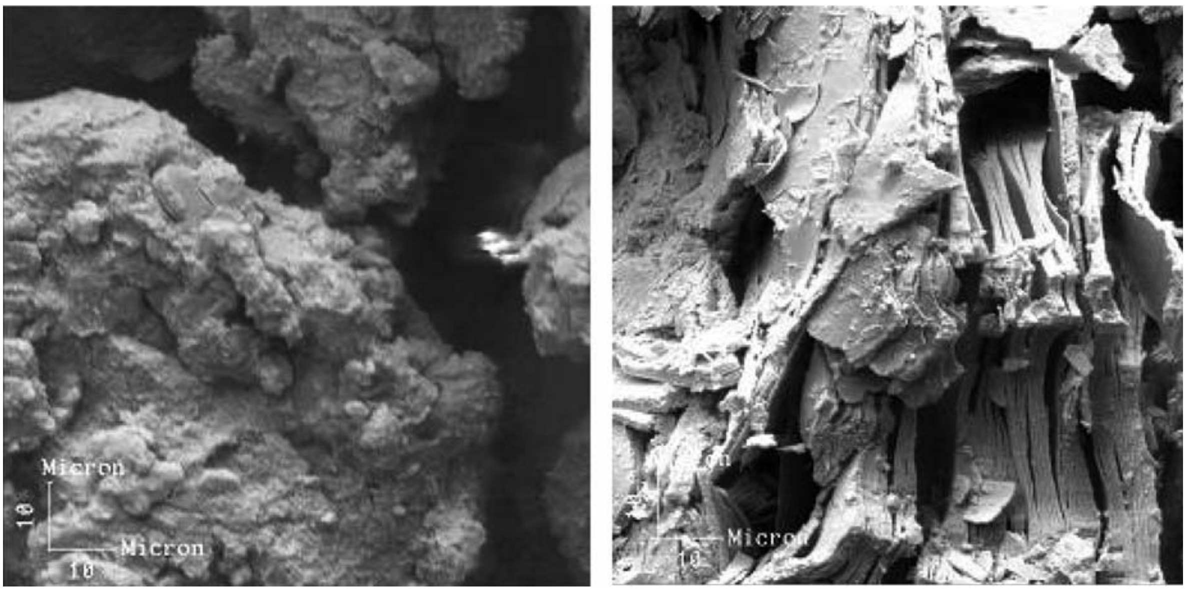


Fig. 9. Scanning electron microscopimages of the lateritic (1 m depth) and saprolitic soil (5 m depth) at Ouro Preto (Futai *et al.* 2004).

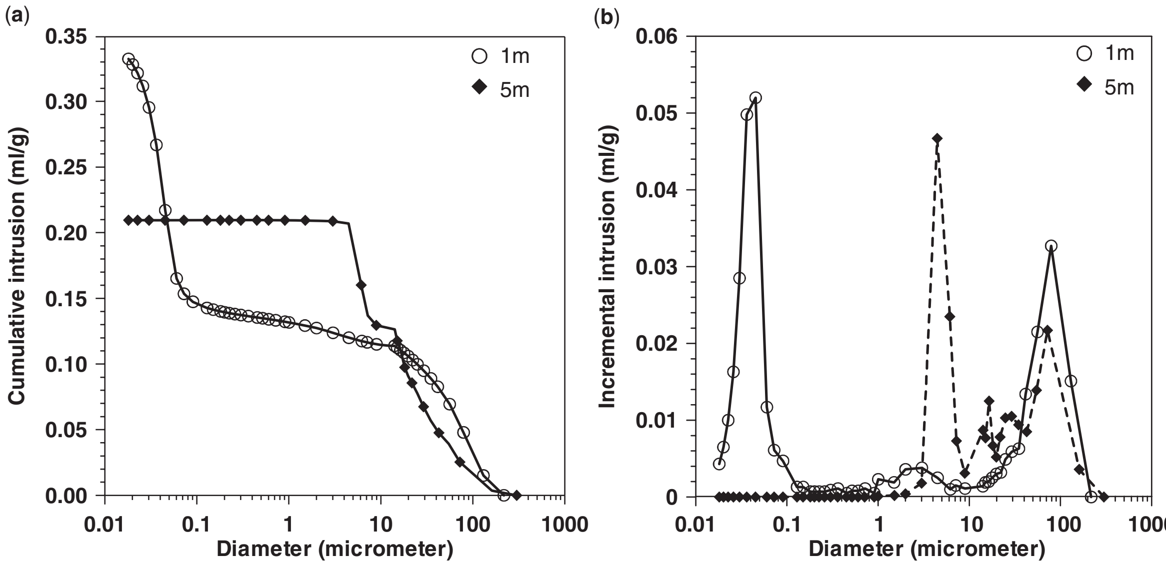


Fig. 10. Pore-size distribution obtained by the mercury intrusion porosimetry technique (Futai *et al.* 2004).

pressures involved. Bishop & Garga (1969) used a triaxial test with a reduced area in the centre of the specimen, but the procedures for this test are cumbersome. Using this technique, Meyer *et al.* (1999) determined the true cohesion of Waitemata clay, an undisturbed residual soil from Auckland, New Zealand. Cohesion intercepts of 13.7 kPa were measured.

A simple way to overcome the experimental difficulty is by means of the 'Brazilian test'. This test is widely used in rock mechanics for the determination of the tensile

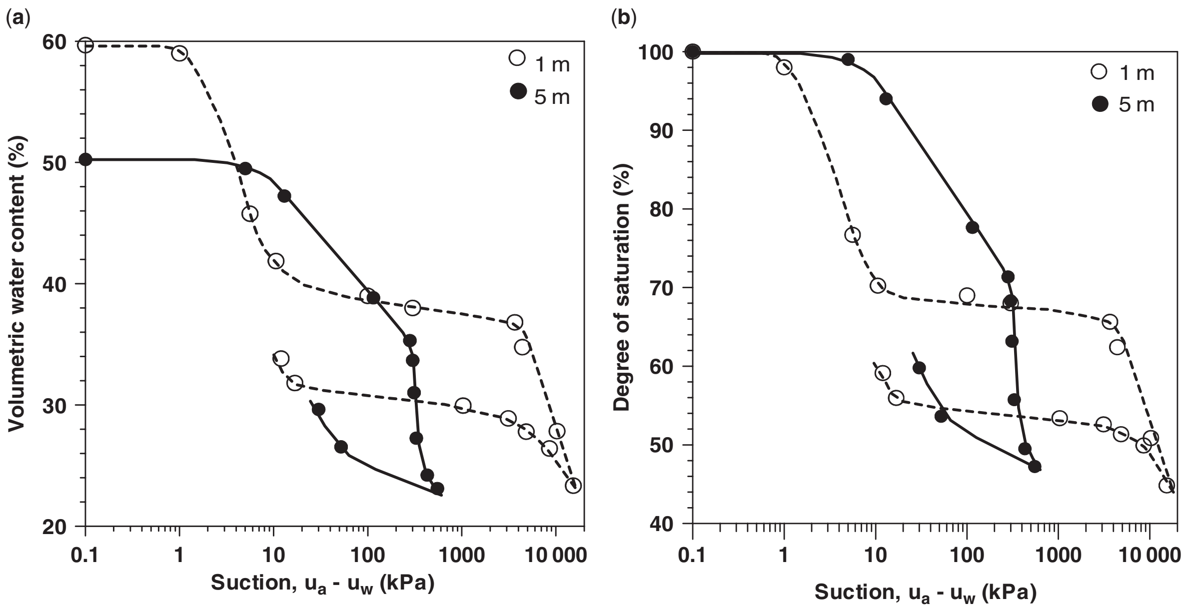


Fig. 11. Soil water retention curve (Futai *et al.* 2004).

Table 2. *Natural void ratios of undisturbed residual or saprolitic soils*

Reference and location	*Soil and rock type*	*Void ratio (e_0)*
Pinto *et al.* (1993), State of São Paulo, BR	Lateritic, migmatite	0.79–1.32
	Lateritic, basalt	1.3–1.6
	Colluvium (lateritic)	1.0–1.76
Clementino & Lacerda (1992), Rio de Janeiro, RJ	Saprolitic soil, granite	0.35–0.65
	Lateritic, granite	0.75–1.0
	Colluvium (lateritic), granite	1.1–1.6
Lacerda & Silveira (1992), Rio de Janeiro, RJ	Saprolitic, granite	1.1–1.2
	Colluvium (lateritic), granite	2.1–2.5
Futai *et al.* (2004), Ouro Preto, State of Minas Gerais	Lateritic, gneiss	1.1–1.5
	Saprolitic, gneiss	0.7–1.0

strength of rock, and was developed to measure the tensile strength of concrete cylinders. It was adapted for testing discs of cylindrical samples cut from undisturbed samples of lateritic soil (Rodriguez 2005). Figure 15 shows the experimental set-up, adapted from rock mechanics laboratory tests. The details of the loading platens can be seen in Figure 16. The soil specimens were discs cut from block samples with diameter (D) of 54 mm and thickness (t) of 27 mm ($D/2$). Loads and vertical displacements were measured by means of a load cell and an displacement transducer. The velocity of axial movement of the loading frame was 0.054 mm min^{-1}, the same as used in direct shear tests on the same soil. The groundwater was at great depth, and could not be sampled; therefore the specimens were immersed in distilled water for 24 h, and tested under water. This procedure was intended to allow all capillary stresses to dissipate. Of course, there would be a difference in the cohesion obtained if the natural groundwater were used, because of the presence of dissolved ions. However, the objective of the tests was to verify the

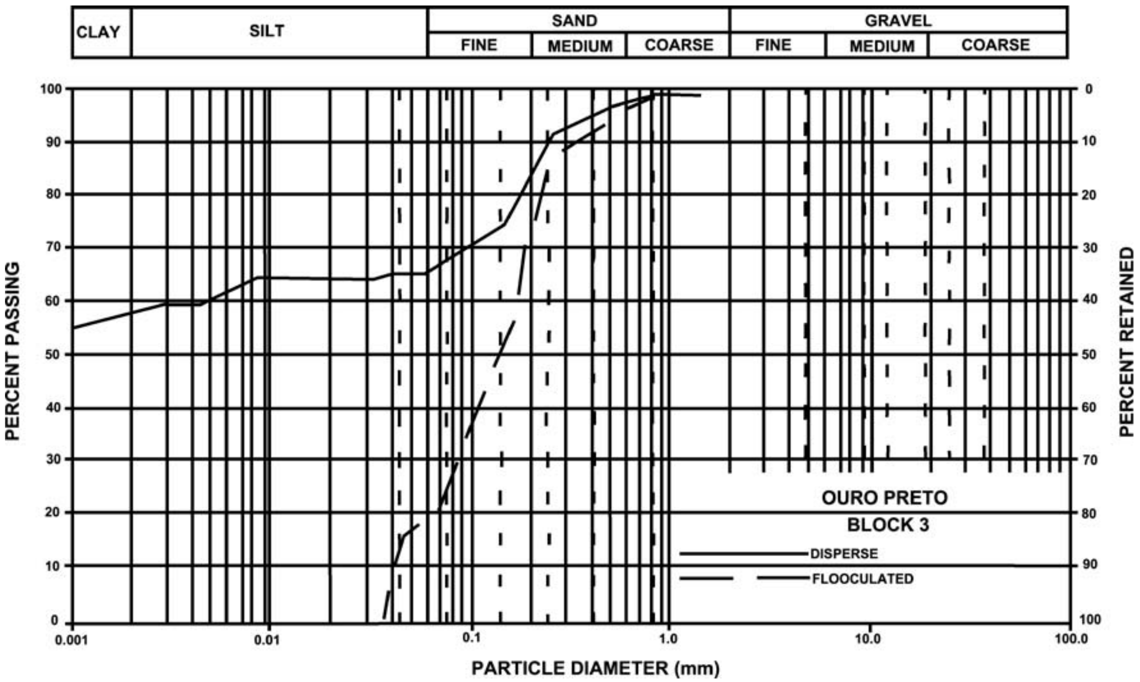


Fig. 12. Grain-size analysis of a lateritic soil without (dashed line) and with (continuous line) dispersing agent (SCS test) (Rodriguez 2005).

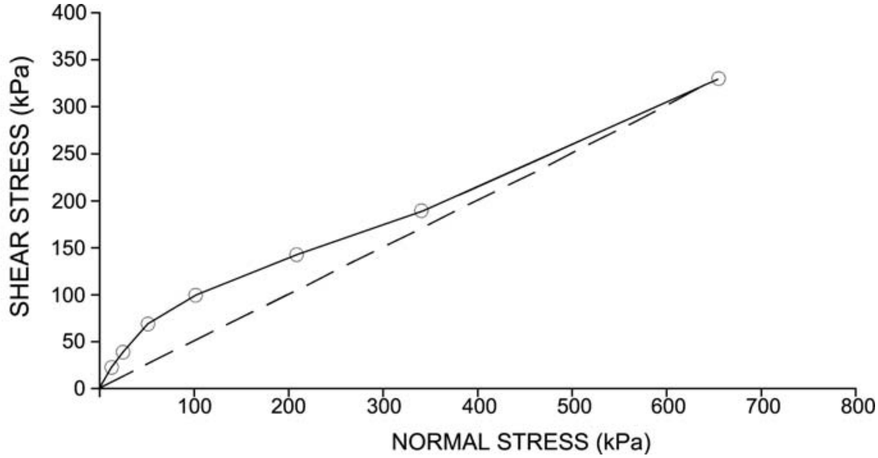


Fig. 13. Mohr envelope of a residual soil from gneiss in saturated direct shear tests (Rodriguez 2005).

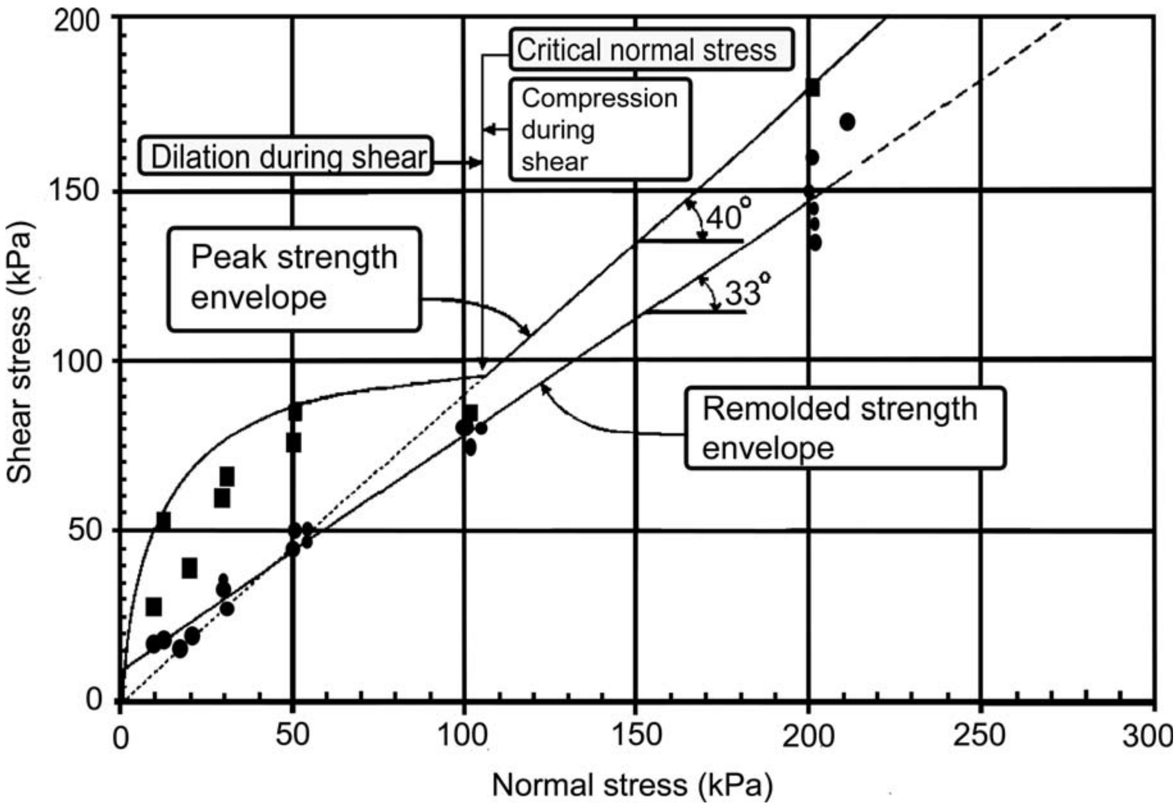


Fig. 14. Bi-segment Mohr–Coulomb failure envelope and remoulded strength envelope for a completely decomposed fine ash tuff in saturated triaxial tests (Gan & Fredlund 1996).

Fig. 15. Experimental set-up of the Brazilian test. Left, test without submersion; right, test with specimen under water (Rodriguez 2005).

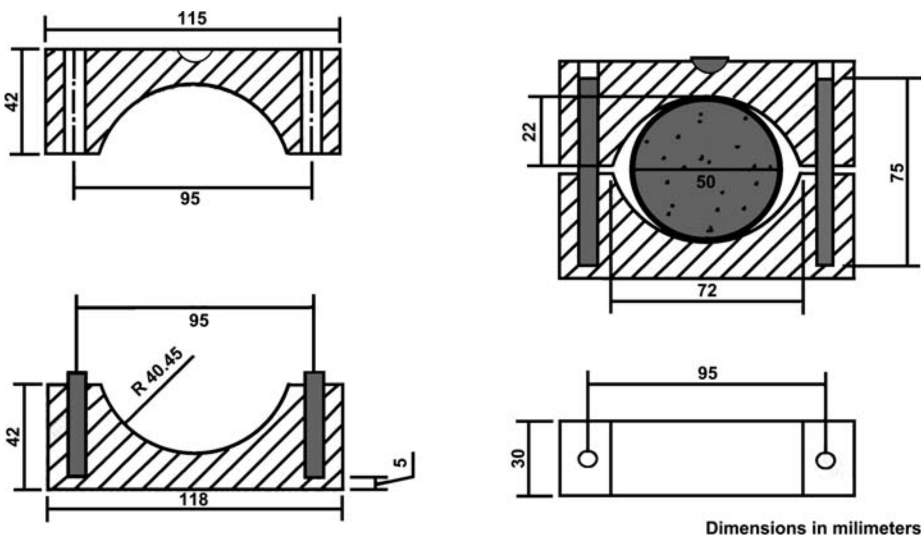


Fig. 16. Loading platens (Rodriguez 2005).

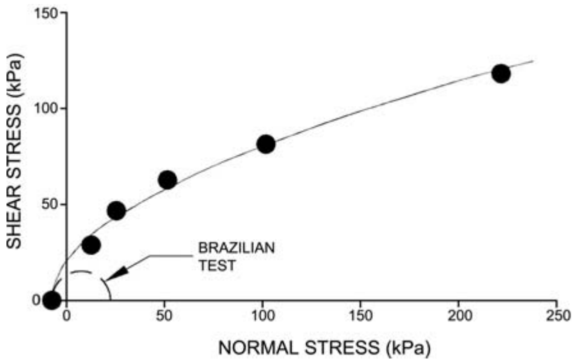


Fig. 17. Mohr envelope of a lateritic soil with true cohesion (Rodriguez 2005).

existence of true cohesion. The load at which the first fissure occurred was identified by a peak in the load v. deformation curve. The tensile strength was calculated by means of the equation

$$\sigma_t = \frac{2P}{\pi D t} \quad (3)$$

where P is the peak force, D is the diameter (in cm) and t is the thickness (in cm).

The curved envelope for soils that do not show cohesion usually is of the form $y = a.x^n$. For soils with true cohesion the equation proposed by Baker (2004) is

$$\tau = 100A\left(\frac{(\sigma + t)}{100}\right)^n \quad (4)$$

where t is the tension intercept on the σ axis, (in kPa), σ is the normal stress (in kPa), τ is the shear stress (in kPa), and A and n are non-dimensional parameters. This equation obeys Mohr's conditions if $A > 0.1$ and $0.5 \leq n \leq 1.0$.

Figure 17 shows the result of triaxial tests and Brazilian tests on a lateritic soil, and Figure 18 shows those on a saprolitic soil from gneiss. The envelopes with cohesion show a similarity to Mohr–Coulomb envelopes of rocks, but the similarity ends here. From rocks to saprolitic soils, cohesion falls to zero. In a further stage, as a result of pedogenetic processes, saprolitic soils turn into lateritic soils, and cohesion is gained through cementation.

Influence of Mohr envelope curves on the stability of shallow lateritic slopes

Steep slopes (angles greater than 30°) are common in granitic–gneissic regions of southern Brazil. The rock is covered by a shallow mantle of residual soil (1–4 m thick). During heavy rainfall the phreatic level may reach

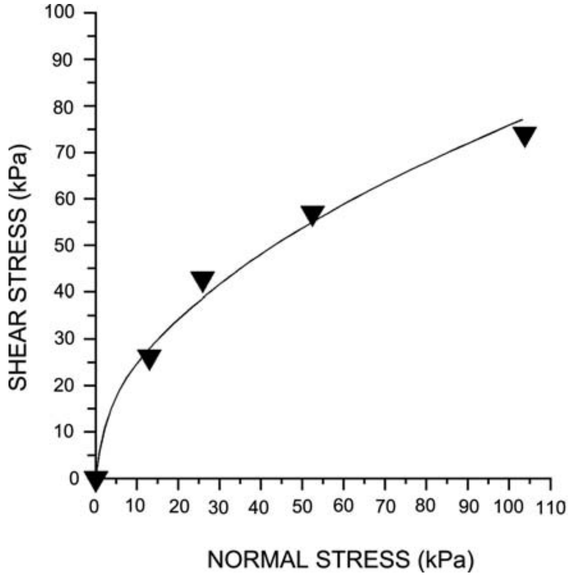


Fig. 18. Mohr envelope of a saprolitic soil without true cohesion (saturated, direct shear tests) (Rodriguez 2005).

depths close to the surface, and as the usual friction angle of these soils is typically in the range 30–40°, the slope may fail. Therefore the existence of a true effective cohesion is crucial in the development of these slides, which are of the so-called 'infinite slope' type and appear as scars on the mountainside when viewed from afar.

Because of the curved Mohr envelopes, the usual linear envelope used in standard stability analysis programs varies depending on the range of depth of the soil profile (this does not happen if the computer program allows a curved strength envelope). Figure 19 shows three Mohr envelopes: one curved, passing through the origin (zero effective cohesion, line A), one curved, with the tension stress considered (line B), and one linear, based on direct shear test results on submerged specimens loaded with normal stresses above 10 kPa (line C).

If one extrapolates linearly the data obtained in the stress range above 20 kPa, the effective cohesion intercept will be 28 kPa and the effective friction angle 29°. If an analysis is made using the infinite slope method with this envelope for very shallow slides, with the phreatic level at the surface and flow parallel to the slope, typically reaching less than 3 m in depth, the result could yield a factor of safety of the order of 1.50 for a natural slope angle of 40°. However, the curved envelope drops sharply below 20 kPa, and if the soil thickness is small, an envelope for the range up to 30 kPa in vertical stress would give, in this case, a cohesion intercept of 10, and an effective friction angle of 53°; a factor of safety of the order of 1.10 would be obtained. Therefore it is recommended to use a curved Mohr envelope in the analysis of shallow slides.

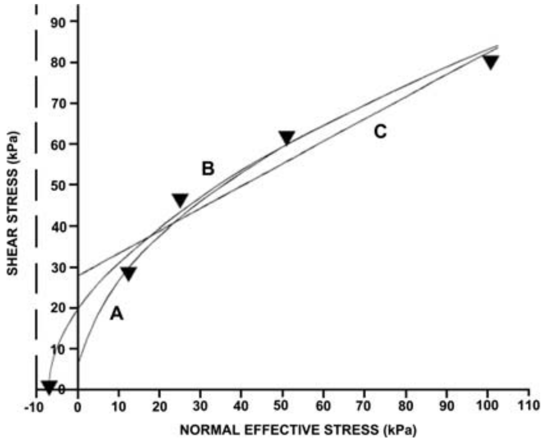


Fig. 19. Mohr envelopes A, B and C in the analysis of an infinite slope (Rodriguez 2005).

Residual friction angle

The movement along a shear surface of a landslide usually is able to reduce the soil shear strength to its residual condition. Leroueil *et al.* (1996) noted that after a first failure, when the peak strength is reached, the reactivation of a landslide can occur if the residual strength is mobilized. Fonseca (2006) analysed two such slides in a residual tropical soil in southern Brazil and showed that this explains the mechanisms of failure observed in the field.

Many researchers have made important contributions to the study of residual strength in recent decades (Lupini *et al.* 1981; Vaughan 1988; Fonseca & Lacerda 2003; Rigo *et al.* 2006). Initially sedimentary clays were studied, and Lupini *et al.* (1981) suggested a band that clays would follow when the residual friction angle is plotted against the clay content of the soil; the higher the clay content, the lower the friction angle. However, since that study a significant amount of data was collected, and Fonseca & Lacerda (2003) and Rigo *et al.* (2006) showed conclusively that lateritic soils behave as a granular soil, and their residual friction angle is independent of the clay content (determined in the usual grain-size tests using dispersing agent). Saprolitic soils have a trend similar to that observed by Lupini *et al.* (1981), but when the mica content of the silt fraction is significant the residual friction angle falls well below the band of Lupini *et al.* This can be seen in Figure 20 (Fonseca & Lacerda 2003).

Conclusions

The study of the properties of tropical soils is relevant particularly in relation to the mechanics of landslides. Regions with high rainfall and subject to severe and frequent rainstorms develop landslides and debris flows that may affect large populations. The initiation of these landslides can be explained when the shear strength characteristics of these soils are better understood. Colluvial slopes in tropical regions have special characteristics, as shown by Lacerda

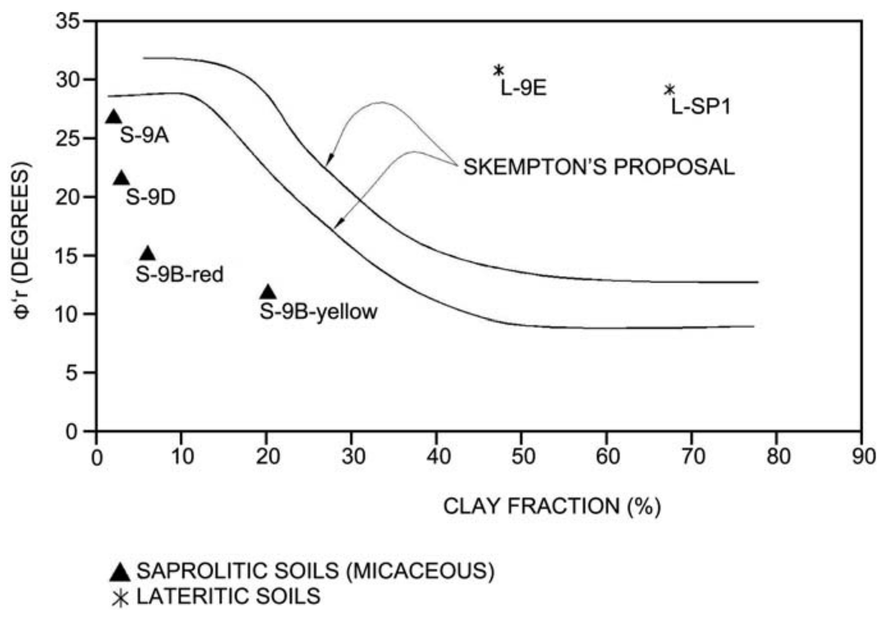


Fig. 20. Residual friction angles of lateritic and saprolitic (micaceous) soils from gneiss (Fonseca & Lacerda 2003).

(2004). Many slides in residual soils are directly related to relict structures inherited from the parent rock, and the residual strength is relevant in these cases. The existence of 'true' cohesion in lateritic soils is particularly important in the initiation of shallow slides.

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