Slope failures in Tertiary OC clays of São Paulo

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ABSTRACT: This paper deals with slope stability in a oddly behaved, expansive, overconsolidated, stiff Tertiary clay of São Paulo, Brazil. A comprehensive site investigation was carried out and involved laboratory and in situ tests. Back-analyses of failures showed two different mechanisms, one leading to shallow failure in the clays owing to expansion, followed by surface degradation or slaking. The other mechanism was lack of shear strength in the clay to resist stresses imposed by a high and steep slope.

RESUMO: Este artigo trata de estabilidade de taludes em uma argila expansiva, sobreadensada, rija do Terciário de São Paulo. Uma ampla investigação foi realizada com ensaios laboratoriais e in situ. Retroanálises da ruptura mostraram dois mecanismos, um levando à ruptura rasa na argila devido à expansão, seguida de degradação da superfície, outro, devido à resistência insuficiente para a argila resistir as tensões devido ao talude projetado.

INTRODUCTION

Geotechnical engineers of São Paulo faced several slope failures along the new Carvalho Pinto Motorway extending from São Paulo northward. The failures occurred in excavated slopes and were triggered by stiff, overconsolidated (OC), Tertiary clays. Most were minor and shallow failures, until a 26 m high slope failed during excavation. Then, Dersa Desenvolvimento Rodoviário SA, the state company in charge of the project, decided to set up an expert committee to carry out additional investigations, to analyse the causes of the failure and to propose solutions and preventive measures for this and other projects in the region. Analysis of failures in OC clays is of a special interest because most Brazilian sedimentary soils are Quaternary (Ortigao, 1995), and data on Tertiary clays are scarce. The work encompassed site investigation and stability analyses. This paper presents additional information to a previous publication elsewhere (Ortigao et al, 1997).

GEOLOGY

The project is located in the Paraiba Valley basin of the Pre-Cambrian Atlantic highlands. This basin covers an area of 20 by 150 km, located north of the City of São Paulo and containing Tertiary and Quaternary alluvial sediment.

The 26 m-high slope failure occurred in the Tremembe Formation, which consists of greyish-green or reddish-brown claystones, clays, and shales interlayered with sandstone and siltstone breccias.

The shales and clays have characteristics of lake deposition and are interbedded with alluvial clay deposits showing cross-stratification. These materials are heavily overconsolidated and have high undisturbed shear strength. Like most Tertiary clays in this region, they are covered by 3 to 10 m of Quaternary red porous clay interlayered with thin (generally 1 to 4 m) sand layers.

Slope failures commonly occur during excavation in these materials. Once the upper soil deposits are removed and the Tertiary clay surface is exposed, the clay swells rapidly and loses strength. Its surface cracks into small, flat pieces, like chips, and this process is locally called *empastilhamento* in Portuguese, i.e., *slaking* in English (Figure 1). This process leads to shallow failures.

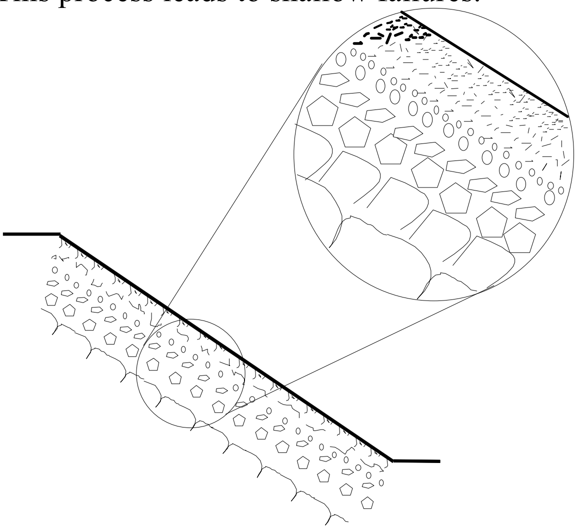

Figure 1 Slaking of the Tertiary clay crust due to swelling

Other problems occur because of the presence of water in the sand layers, which leads to piping. Water flowing through or on the slaked clay surface contributes to reduced shear strength.

SLOPE FAILURE

Figure 2 shows a cross-section of the 26 m high slope just before failure. A series of boreholes drilled after failure showed five soil layers. At the top is a porous red clay, having SPT (N) values from 4 to 8 blows/30 cm. The porous clay is very typical of São Paulo and other regions of the central plateau highlands of Brazil and has been studied in detail at other sites (Ortigao et al, 1995). The porous nature of this clay results from leaching of soluble salts and precipitation a few metres below, which causes laterization.

The porous clay overlays a loose to medium, fine, white sand, which in turn overlays Tertiary stiff clay having N values ranging from 17 to 27 blows/30 cm. This clay was greyish green at one side of the slope and reddish brown some 200 m away. When exposed, both showed signs of slaking. Generally, they looked alike, except for colour. This layer overlays a very dense white sand layer that, in turn, overlays an olive-green, very stiff Tertiary clay. Both had N values greater than 30 blows/30 cm.

The water level was perched on the upper sand layer. A lower water level was detected later at the lower, very dense sand layer.

The excavation started at elevation 650 m. Design was based on Dersa's previous experience in the region and encompassed

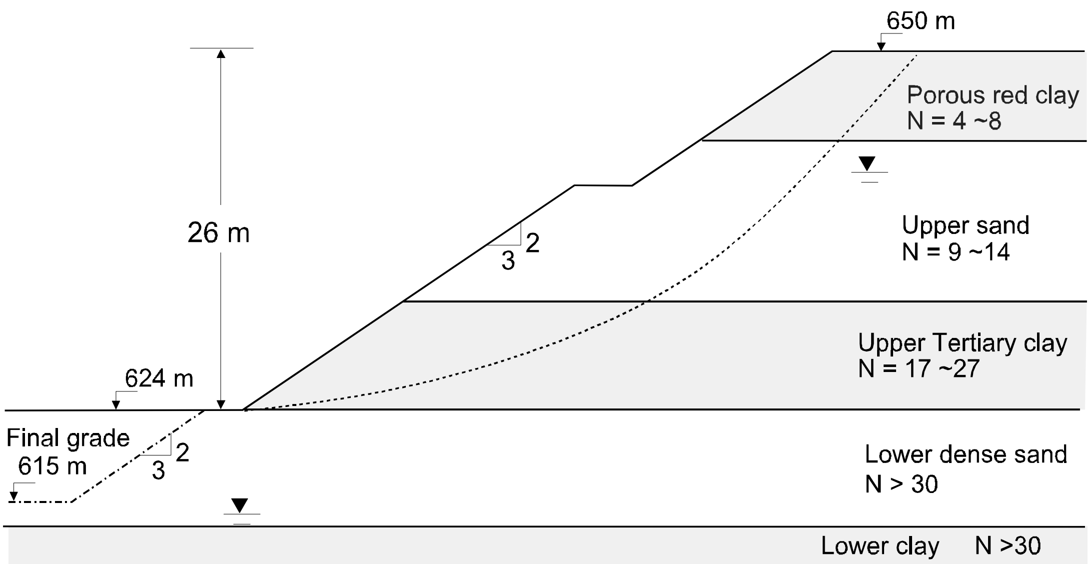

Figure 2 Failure in a 26 m high slope (initial design)

Table 1 Atterberg limits and mineralogy

Clay	% < 2 μm	w (%)	LL (%)	PL (%)	PI (%)	Smectite (%)	Kaolinite (%)	Illite (%)
Greyish green	77	38	116	35	81	55	25	20
Reddish brown	79	40	103	35	68	60	40	0

Table 2 Strength parameters from triaxial tests

Clay	UU		CIU		CID	
	c_u (kPa)	ϕ_u °	c' (kPa)	ϕ' °	c' (kPa)	ϕ' °
Greyish green	5-10	25	32	19	53	19
Reddish brown	20	16.5	54	22.5	32	20

excavation of a 3:2 (horizontal:vertical) slope. Works proceeded quickly until elevation 624 m was reached, when it was halted for the placement of a 4m-thick clay liner. This liner (not shown in Figure 2) was designed to limit swelling and slaking of the Tertiary clay surface. These works had just started when major slope failure occurred.

SITE INVESTIGATION

Site investigation for initial design was limited: it consisted of just one SPT borehole. No problems were anticipated. After failure, the expert committee decided to carry out a comprehensive site investigation program consisting of additional boreholes, installation of several Casagrande-type piezometers, in situ tests with the Marchetti dilatometer, block sampling, and laboratory tests.

Laboratory tests

Four block samples were obtained in the Tertiary clay, two in the greyish-green and the others in the reddish-brown clay. Laboratory tests included index tests; X-ray diffractometry tests; and unconsolidated undrained (UU), isotropically consolidated undrained (CIU), and isotropically consolidated drained (CID) triaxial tests.

Index-test results are summarised in Table 1. The water content (w) is close to 40 %; the liquid limit (LL) ranges from 105 to 115 %; the plastic limit (PL) is around 35 % and the plasticity index (PI) varies from 70 to 80 %. The clay content (percent of material finer than 2 μm) is nearly 80 %. The unit weight (γ) was 18 kN/m^3.

Measurements of the degree of saturation, given in detail by Ortigao et al (1997) indicated values from 80 to 95%.

Results of X-ray diffractometry tests in the Tertiary clay are presented in Table 1, where a large proportion of the expansive mineral smectite was detected. This explains the swelling characteristics of this clay.

Triaxial testing was carried out on unsaturated specimens, since it is unlikely that the Tertiary clay could achieve full saturation. Typical results are presented in Figure 3 and Figure 4 and summarised in Table 2.

Plots of strength envelopes and effective stress paths utilise the following co-ordinates: t is the shear strength at failure, s'_{ff} is the *estimated* normal mean effective stress and s_{ff} the corresponding mean total stress. The correct value of the effective stresses may be different from the *estimated* values from pore pressures measurements, due to lack of full saturation.

The stress paths shown in Figure 3 for CIU tests are typical of overconsolidated clay with very low or slightly negative pore pressures, except for the specimen with the larger confining stress, in which pore pressures were positive close to the end of the tests.

UU triaxial strength envelopes showed a low c_u and a relatively large ϕ_u. The sloping envelope ($\phi_u \neq 0$) can be caused by unsaturation in a low stress range. In fact, specimens showed

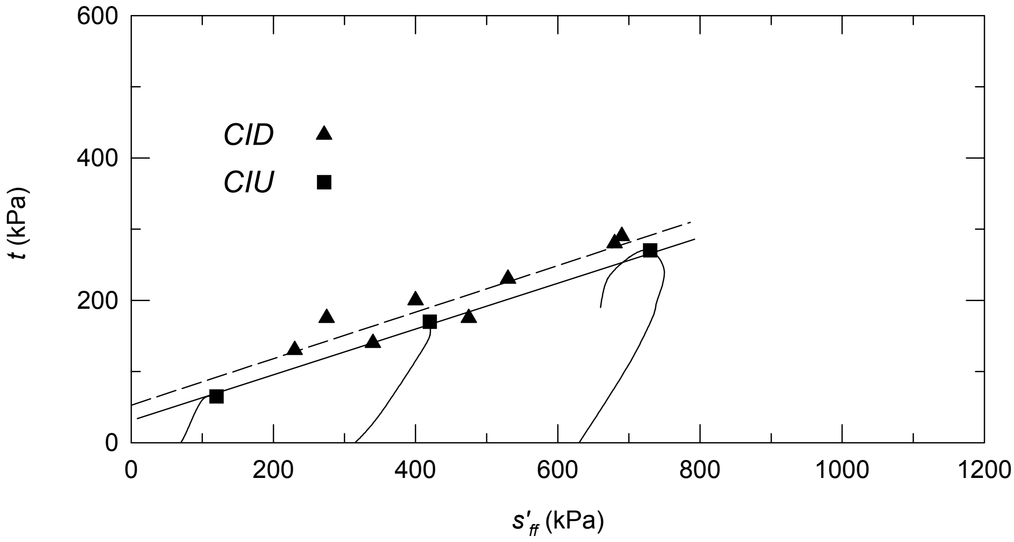

Figure 3 Triaxial tests in the Tertiary clay

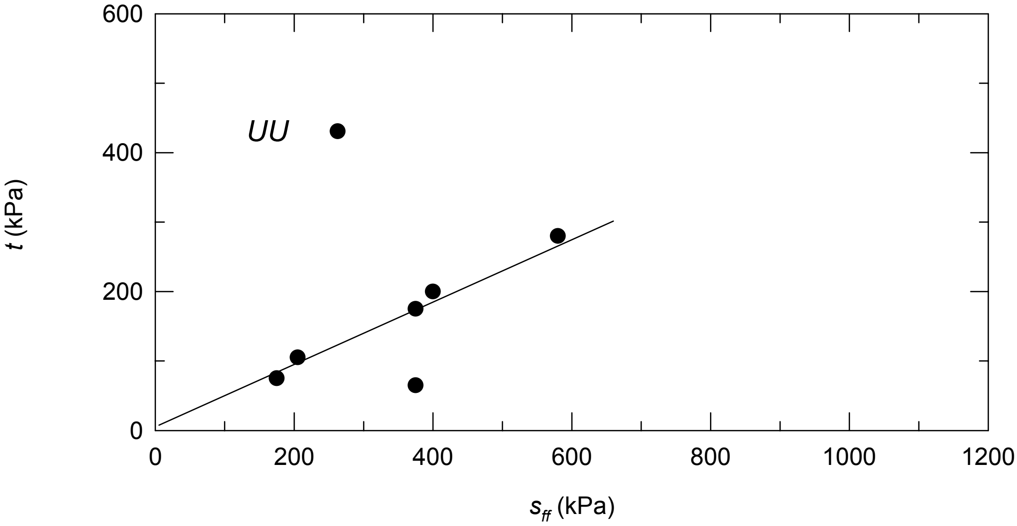

Figure 4 UU tests in the greyish green Tertiary clay

a relatively low degree of saturation at the beginning of tests and the stress range that matched field conditions is probably much less than maximum past pressures, as indicated by the dilatometer tests, discussed in the next paragraph.

Dilatometer tests

Three Marchetti dilatometer test (DMT) boreholes were carried out.

The DMT gives the following indexes: the material index I_D, the horizontal stress index K_D and the dilatometer modulus E_D (Marchetti, 1980). Marchetti proposed a series of correlations based on Italian soils for estimating the soil type, unit weight, the in situ stress ratio K_0, the overconsolidation ratio *OCR,* the undrained strength for clays c_u, the friction angle for sands and the one-dimensional compression modulus *M.* The DMT has been used successfully in other tropical Brazilian soils such as porous clays, (Ortigao, 1994, Ortigao et al, 1996), but never before in Tertiary clays. However, even though the correct value given by the DMT correlations for a *new* soil

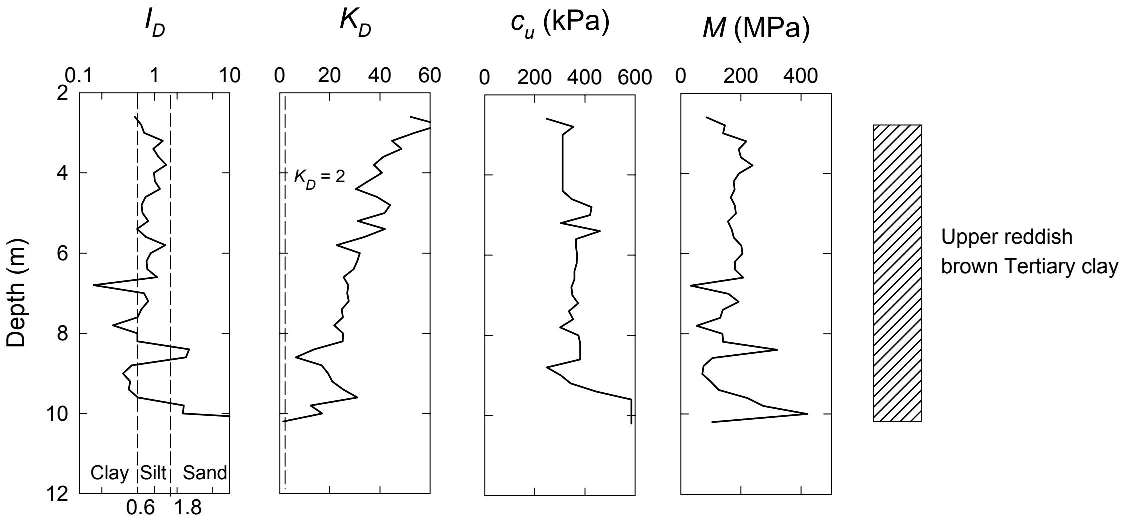

Figure 5 DMT profile in the upper reddish brown Tertiary clay

may not be corrected, the *trend* given by the DMT can be trusted, as observed in a series of references dealing with the DMT (*e.g.*, Lunne et al, 1989) and confirmed in other tropical soils in Brazil (Ortigao, 1994, Ortigao et al, 1996).

Data from one DMT borehole are presented in Figure 5. The upper clay layer presents values of undrained strength c_u of 300 kPa, approximately constant with depth. The one-dimensional modulus M is around 200 MPa. K_D gives a good indication of stress history of this clay, since it is directly related to OCR. High K_D values indicate high OCR, and when $K_D \simeq 2$, the clay is normally consolidated. The K_D plot indicates that the clay is strongly OC at the top, and tends to NC at the bottom.

Marchetti et al (1994) pointed out that a sharp drop of K_D value in an OC clay may indicate the location of an ancient scar left by a slip surface, due to slip, remoulding, and reconsolidation. This may explain the drop in K_D at 9 m depth Figure 5. The drops in M values at 7 and 8 m depths in this figure can be explained by corresponding changes in I_D values.

The stress history indicated by the DMT seem to be in agreement with the geological interpretation for this kind of Tertiary deposit, *i.e.*, heavily overconsolidated.

A check on the agreement of DMT and UU triaxial strength data in the upper Tertiary clay layer is presented in Figure 6. Strength from laboratory tests in the greyish green clay was obtained for initial estimated total overburden stresses. The agreement of UU triaxial and DMT data is remarkable, which is an indication

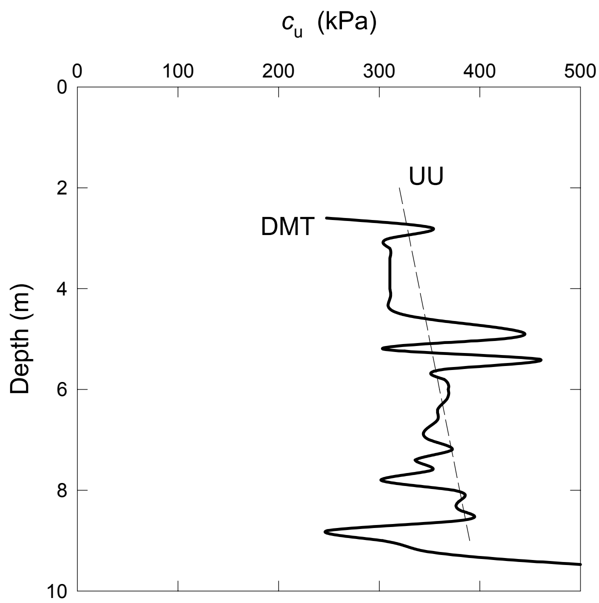

Figure 6 Strength from DMT and lab tests in the upper Tertiary clay

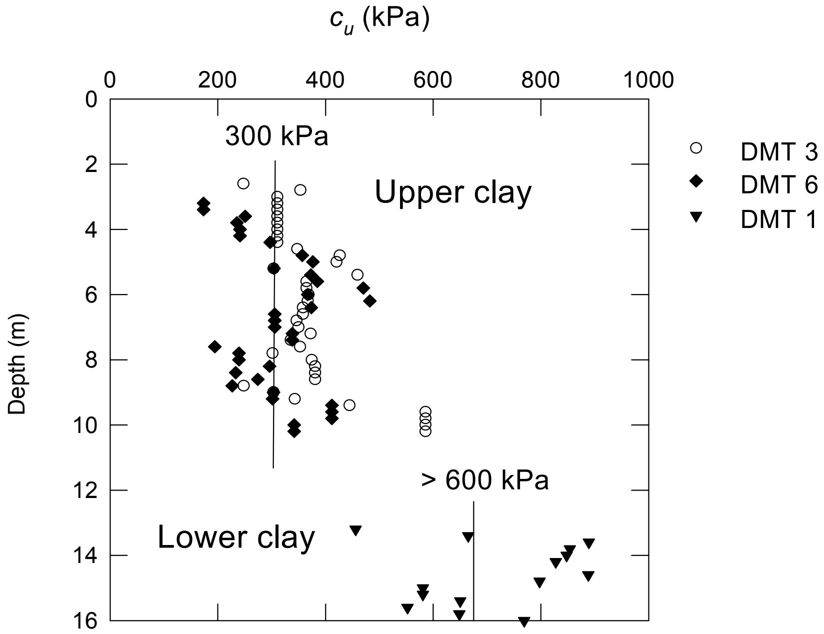

Figure 7 Shear strength from the DMT at the upper and lower Tertiary clay layers

that the DMT gave good results. However, the same attempt to compare CIU and CID tests strength data was unsatisfactory, probably due to poor evaluation of in situ stresses and pore pressures.

Figure 7 compares c_u data from DMT tests in the upper and lower Tertiary clay layers. The upper clay gives c_u around 300 kPa; the lower one, twice that value.

WATER TABLE IN THE SAND LAYERS

After the major failure, two measures were carried out to control ground-water level in the slope. Field inspection showed water flowing from the upper sand layer. Therefore, on the suspicion of perched water over the upper clay, a series of sub horizontal drains 12 m long and 50 mm in diameter were installed in 75 mm boreholes at 5 m spacing (Figure 8). As water

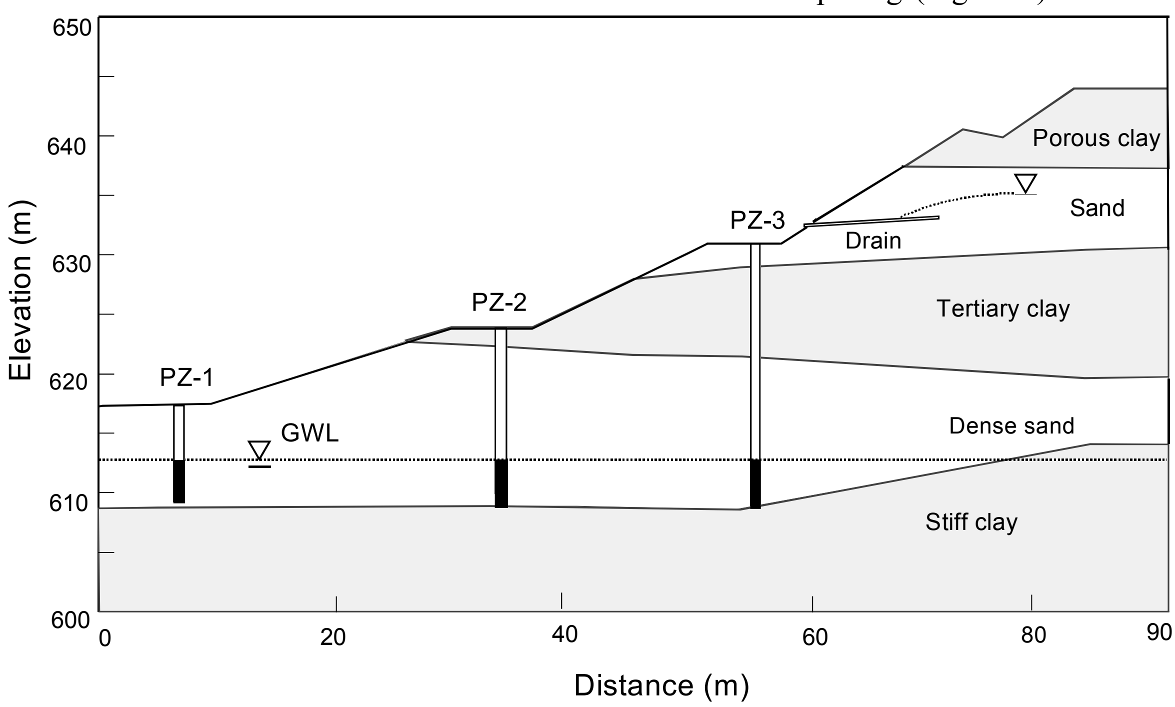

Figure 8 Ground water level in the sand layers

Table 3 Soil parameters for stability analyses

Soil layer	Cohesion	Friction angle	Unit weight	Assumed behaviour	Pore pressures
	(kPa)	(degrees)	(kN/m^3)		
Porous clay	20	26	17	drained	none
Upper sand	0	30	18	drained	1 m below top
Upper Tertiary clay	*Unknown*	*Unknown*	18	undrained or drained	*Unknown*
Lower dense sand	0	30	18	drained	at elev. 613 m
Lower very stiff clay	600	0		undrained	none

Table 4 Results of the back-analyses of the major failure

Strength assumption	**c_u or c'**	**ϕ_u or ϕ'**	**Porepressures**	**FS**
	kPa	degrees	kPa	
UU	55	0	nil, undrained	1.044
UU	0	25	"	0.977
UU	5	25	"	1.081
UU	10	25	"	1.136
CIU	32	19	nil, drained	1.261
CID	55	18	nil, drained	1.383

flowed through many of these drains, this was considered to be effective in reducing pore pressures near the slope face.

There was also concern about pore pressures in the lower sand layer at the toe of the final excavation level. Consequently, the groundwater level in this layer was investigated by using six Casagrande piezometers split into two instrumented sections. The layout of one section is plotted in Figure 8. The water level of the lower sand layer was at elevation approximately 613 m, below the final excavation grade and, therefore, was of little concern for this slope.

STABILITY ANALYSES AND DESIGN

Back-analyses of failures

The shear strength of the upper Tertiary clay was assessed through back-analyses of two slope failures, according to the profile shown in Figure 2. The major one, described earlier in this paper, presented a deep slip surface in the Tertiary clay and it is unlikely that slaking had extended to this depth. Therefore, this analysis can be used to assess the *intact* shear strength of the Tertiary clay.

There was no field evidence that the failure surfaces departed from circular shape, therefore slip circles were considered.

Stability analyses used the simplified Bishop method through *Rstabl* computer program (Ortigao et al, 1995). Only analyses for the greyish-green clay will be discussed.

Table 3 gives assigned soil parameters. Data for the porous clay were based on previous studies at other sites (Ortigao et al, 1996), which enabled assignment of drained behaviour for this layer. Sand strength was estimated from correlations and experience from other sites (*e.g.* Ortigao, 1995). Therefore, the upper Tertiary clay strength was the unknown in the back-analyses.

Strength of the intact clay

Results of the back-analyses of the major failure are given in Table 4 and in Figure 9.

Effective-stress analyses of the Tertiary clay conducted using CIU and CID strength and zero pore pressures (Table 4) showed high FS values, certainly due to the difficulty in evaluating pore pressures in a stiff clay subjected to unloading. Therefore, the only practical solution is to analyse the Tertiary clay in terms of total stresses.

Several alternative UU strength values were assigned for the Tertiary clay: UU triaxial data (c_u from 0 to 10 kPa, $\phi_u = 25^o$, Figure 4) and a constant c_u value, with $\phi_u = 0$. This last assumption was considered in the early stages of the work, before the laboratory test results became available.

Results in Table 4 demonstrate that UU triaxial strength with $c_u = 5$ kPa and $\phi_u = 25^o$ leads to a factor of safety (FS) close to one at failure. On the other hand, keeping $\phi_u = 0$, the resulting c_u that leads to FS = 1 is 55 kPa, which is too low, as compared to the c_u given by the DMT of 300 kPa. Therefore, the UU triaxial strength data probably are appropriate to represent the shear strength in the upper Tertiary clay.

Final design

The final design consisted of flattening the slopes, adding 4m-wide berms, surface and deep drainage, and vegetation. At the toe, the slopes were inclined at 3:1 (horizontal:vertical) in the lower dense sand and in the upper Tertiary clay. Above the upper Tertiary clay, the slopes were 3:2. This cross section resulted in adequate FS values as indicated in Figure 10. Toe and middle circles led to FS greater than 1.5.

Slaking of the clay surface was prevented by the placement of a 4 m wide compacted clay liner, as indicated in Figure 11.

CONCLUSIONS

The investigation of the causes of failure of a 26 m high slope in OC clays Tertiary clays of São Paulo exposed two different processes: slaking of the clay surface and UU type shear strength, which caused the deep-seated failure. Back-analyses showed that the deep failure could be explained with UU laboratory strength for the OC clay employing a low value for c_u and $\phi_u > 0$, due to unsaturation. CIU and CID triaxial tests are inappropriate for this clay.

The DMT confirmed the existence of strong overconsolidation in the Tertiary clay and yielded undrained strength data that matched laboratory UU strength. Therefore, the DMT is recommended in similar investigations in this material. However, the undrained strength c_u values given by this instrument cannot be used in stability analyses, since the clay strength was

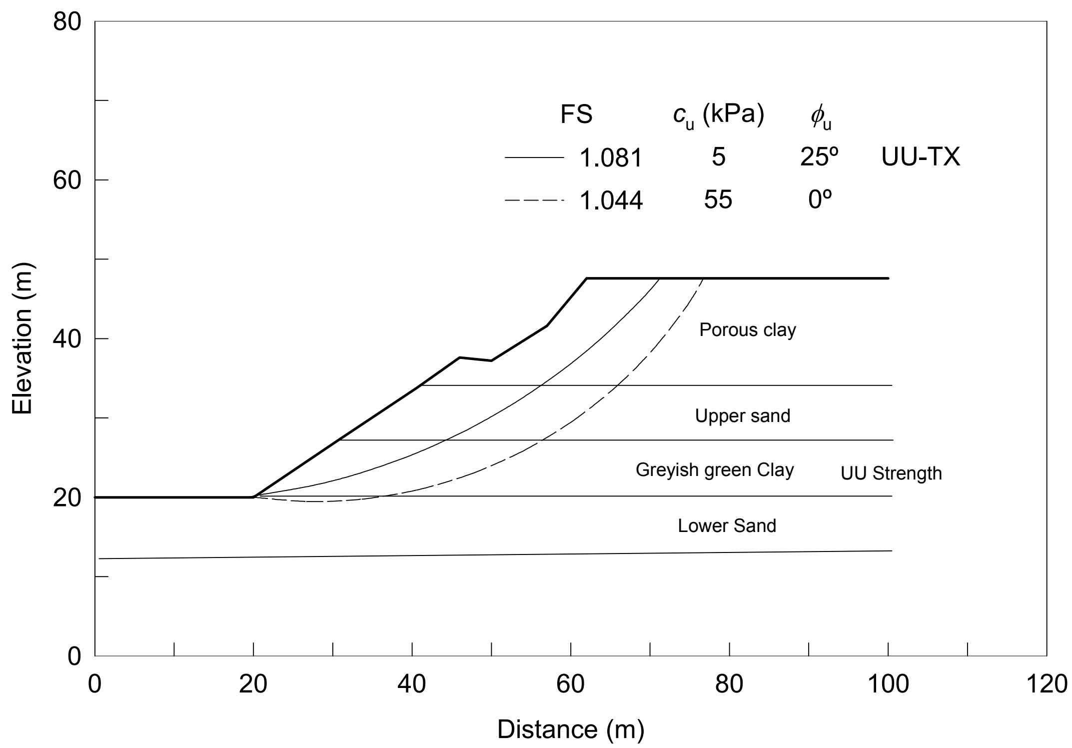

Figure 9 Back-analysis of the major failure

described by a c_u, ϕ_u envelope, with $\phi_u > 0$.

The final design achieved stability by flattening the slopes until a minimum factor of safety of 1.5 was obtained. Slaking was prevented by a 4 m thick clay lining. Surface drainage and deep drainage in the sand layers was adopted.

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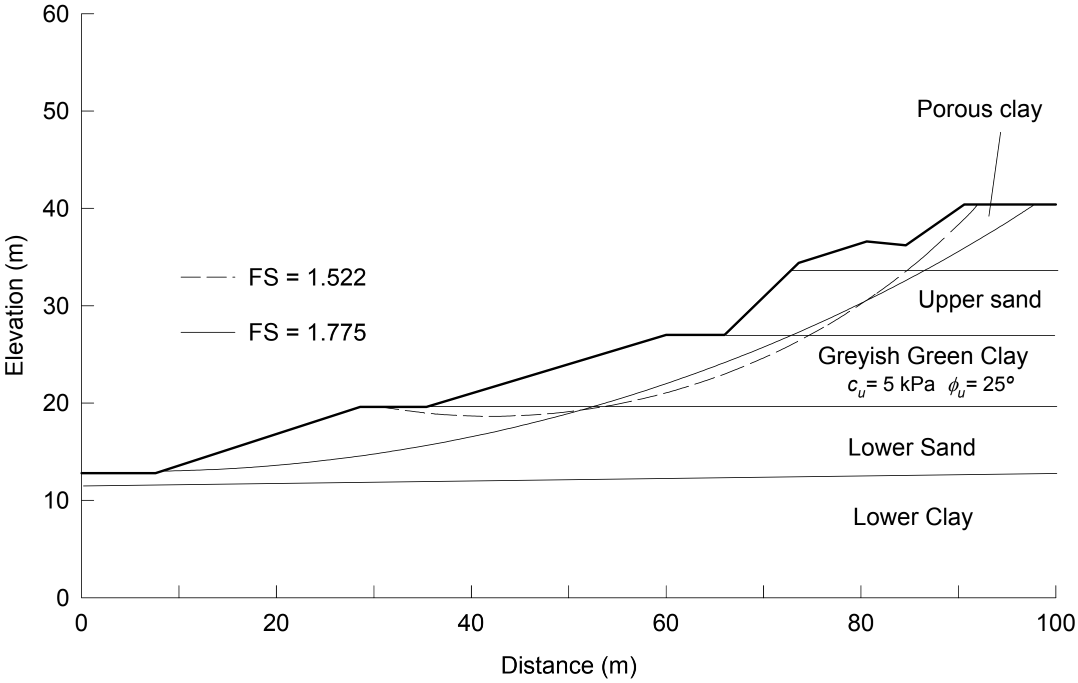

Figure 10 Stability analysis for the final design

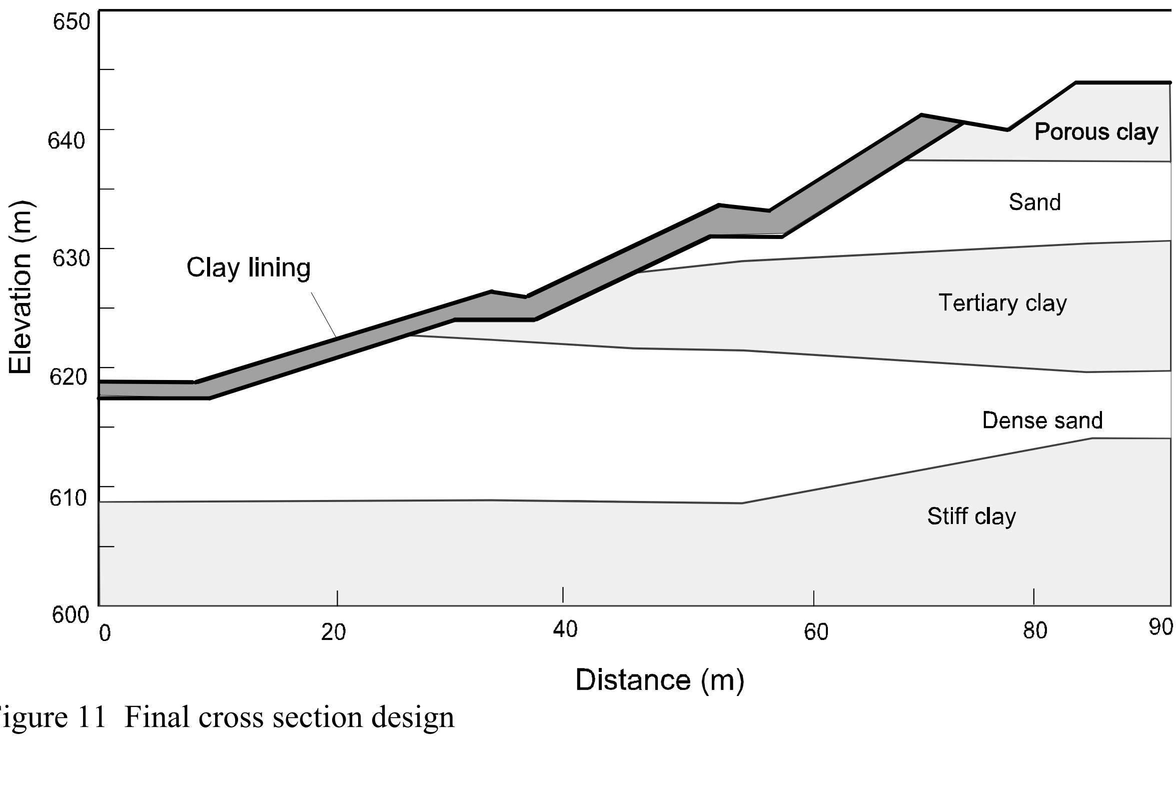

Figure 11 Final cross section design

in Hong Kong, where the first author spent the early months of 1996 and 1997 as Visiting Fellow to the Department of Building and Construction of the City University of Hong Kong.

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