Slope Failures in Tertiary Expansive OC Clays

By J. A. R. Ortigao,[1] T. R. R. Loures,[2] C. Nogueira,[3] and L. S. Alves[4]

Abstract: This paper deals with slope stability in a oddly behaved, expansive, overconsolidated, stiff Tertiary clay of São Paulo, Brazil. The properties were not fully recognized until a recent major failure occurred during excavation on a 26-m-high, 250-m-wide slope constructed for the new Carvalho Pinto Motorway. A comprehensive site investigation was carried out and involved laboratory and in situ tests and successfully employed the Marchetti dilatometer. Back analyses of failures showed two different mechanisms, one leading to shallow failure in tertiary 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. This paper gives site investigation data, discusses the causes, and back analyses of failures, and presents the final slope design.

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. In response, Dersa Desenvolvimento Rodoviário SA, the state company in charge of the project, decided to set up an expert committee to carry out additional investigations in order to analyze 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 summarizes findings and conclusions.

GEOLOGY

The project is located in the Paraiba Valley basin of the Precambrian 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 (Fig. 1). 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, or ''slaking'' in English (Figs. 2 and 3). This process leads to shallow failures.

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 AND SITE CONDITIONS

Fig. 4 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 per 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 meters 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 per 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 color. This layer overlays a very

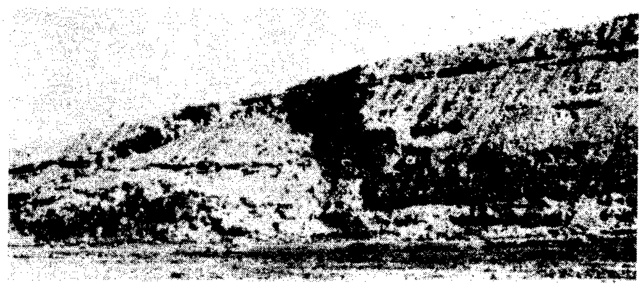

FIG. 1. Failure in OC Tertiary Clay Excavated Slope

FIG. 2. Slaking of Clay Surface

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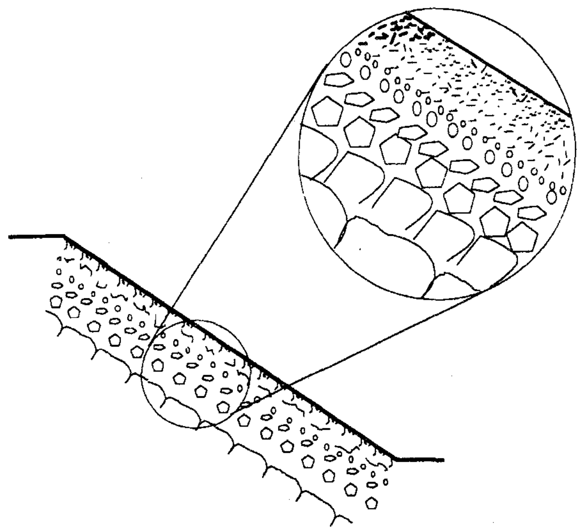

FIG. 3. Slaking of Tertiary Clay Crust due to Swelling

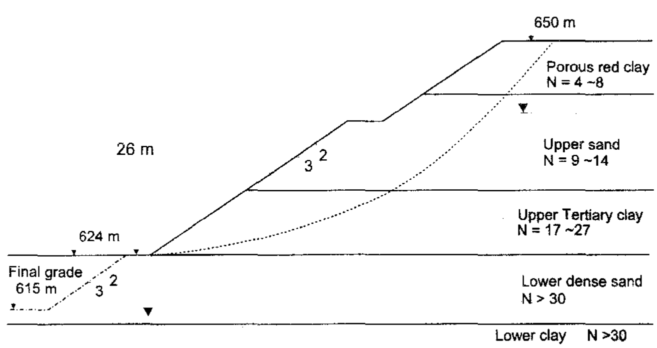

FIG. 4. Failure in 26-m-High Slope (Initial Design)

dense white sand layer that, in turn, overlays an olive-green, very stiff Tertiary clay. Both had N values greater than 30 blows per 30 cm.

The water level was perched at the upper sand layer. A lower water level was detached 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 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 4-m-thick clay liner. This liner (not shown in Fig. 4) 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 Casagrade-type piezometers, in situ tests with the Marchetti dilatometer, block sampling, and laboratory tests.

TABLE 1. Atterberg Limits and Mineralogy

Clay (1)	% < 2 μm (2)	*w* (%) (3)	*LL* (%) (4)	*PI* (%) (5)	*PI* (%) (6)	Smectite (%) (7)	Kaolinite (%) (8)	Illite (%) (9)
Greyish green	77	38	116	35	81	55	25	20
Reddish Brown	79	40	103	35	68	60	40	0

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; unconsolidated undrained (UU) tests; isotropically consolidated undrained (CIU) tests; and isotropically consolidated drained (CID) triaxial tests.

Index test results are summarized in Table 1. The water content w is close to 40%; the liquid limit LL ranges from

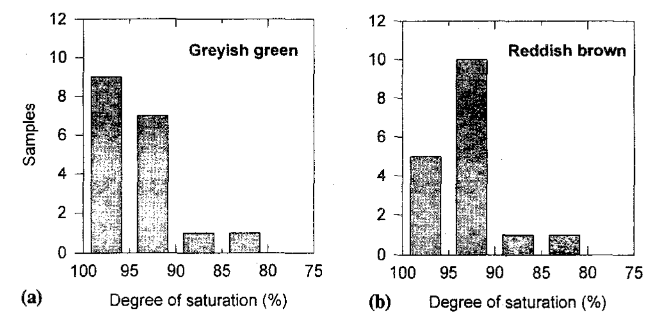

FIG. 5. Degree of Saturation

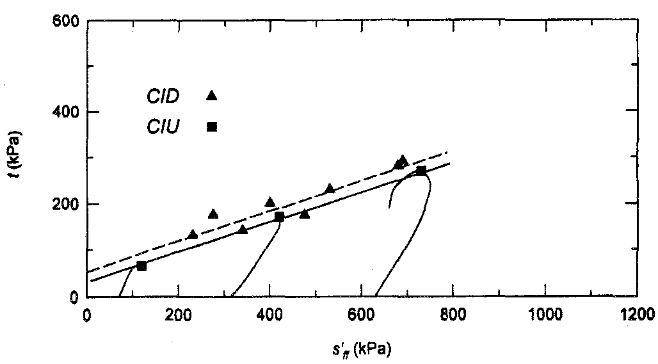

FIG. 6. Triaxial Tests in Greyish Green Tertiary Clay

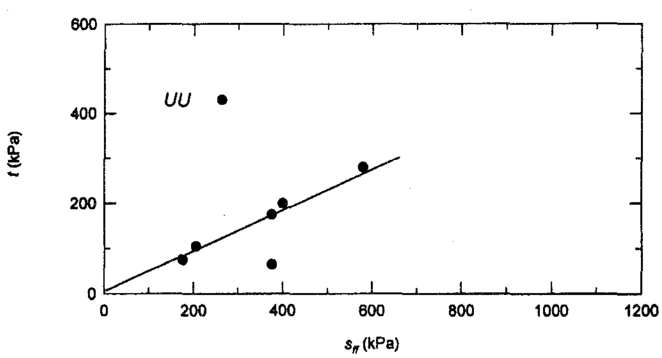

FIG. 7. UU Tests in Greyish Green Tertiary Clay

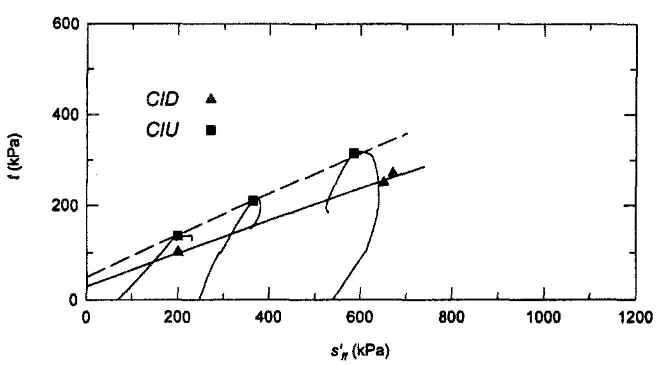

FIG. 8. CIU and CID Triaxial Tests in Reddish Brown Tertiary Clay

105% to 115%; the plastic limit PL is around 35%; 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 S are presented in Fig. 5. Values ranged from 80% to 95% but most values are in the 90% to 95% range. Results of X-ray diffractometry tests in the Tertiary clay are presented in Table 1, where a large

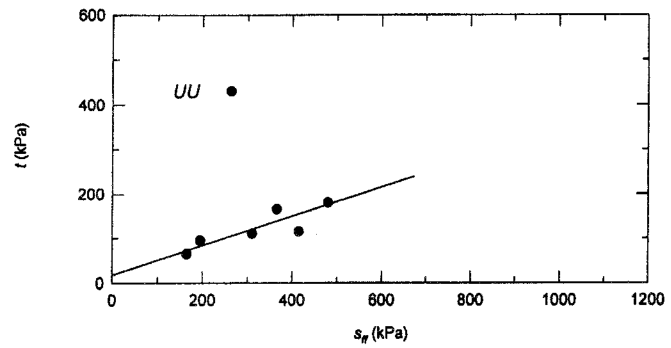

FIG. 9. UU Triaxial Tests, Reddish Brown Tertiary Clay

TABLE 2. Strength Parameters from Triaxial Tests

Clay (1)	UU c_u (kPa) (2)	UU ϕ_u° (3)	CIU c' (kPa) (4)	CIU ϕ'° (5)	CID c' (kPa) (6)	CID ϕ'° (7)
Greyish green	5–10	25	32	19	53	19
Reddish brown	20	16.5	54	22.5	32	20

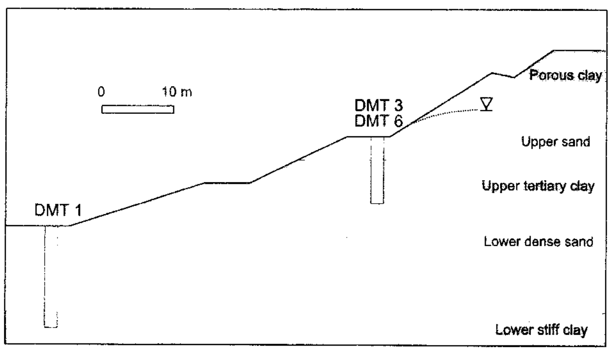

FIG. 10. DMT Test Locations

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. Strength parameters are presented in Figs. 6–9 and summarized in Table 2. Plots of strength envelopes and effective stress paths utilize the following coordinates: t is the shear strength at failure; s'_{ff} is the estimated normal mean effective stress; and s_{ff} is 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

$$s'_{ff} = \frac{\sigma'_1 + \sigma'_3}{2}; \quad t = \frac{\sigma'_1 - \sigma'_s}{2} \qquad (1, 2)$$

The stress paths shown in Fig. 6 and in Fig. 8 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 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 placed at the approximate locations indicated in Fig. 10. One DMT borehole was located at the toe of the slope to reach the lower clay layer, and two others were placed in the middle for testing the upper Tertiary clay.

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

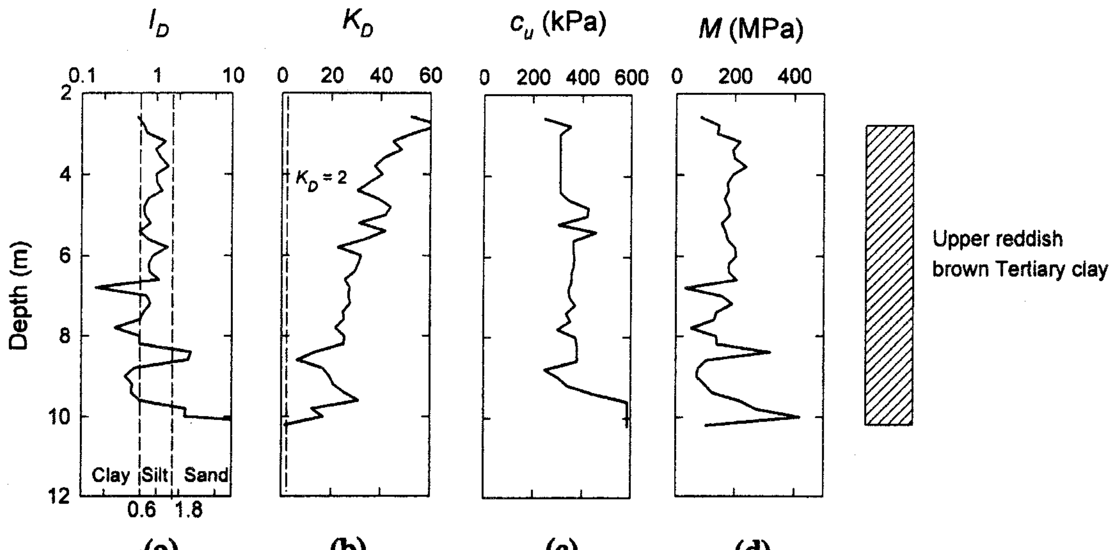

FIG. 11. DMT Profile in Lower Stiff Tertiary Clay (DMT 1)

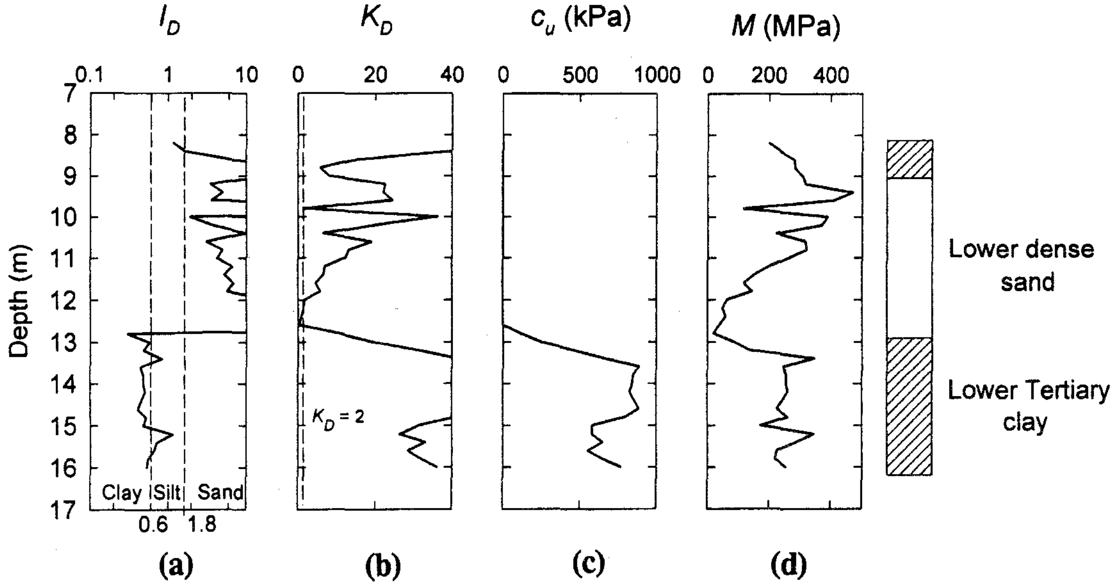

FIG. 12. DMT Profile in Lower Stiff Tertiary Clay (DMT 1)

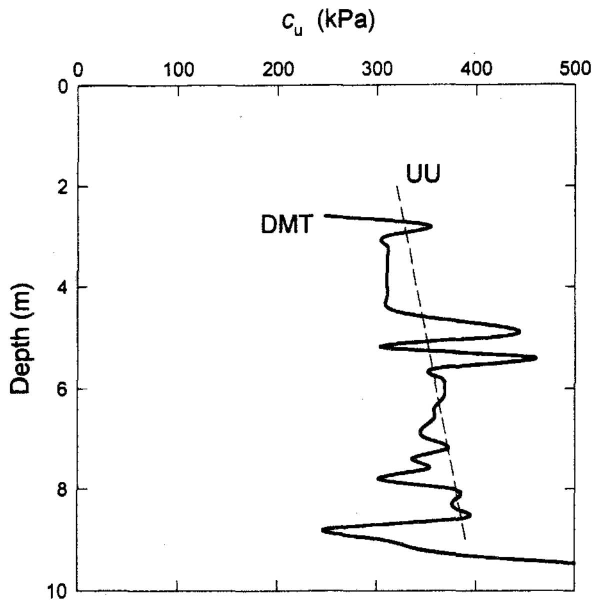

FIG. 13. cu from Field and Lab Tests in Upper Tertiary Clay

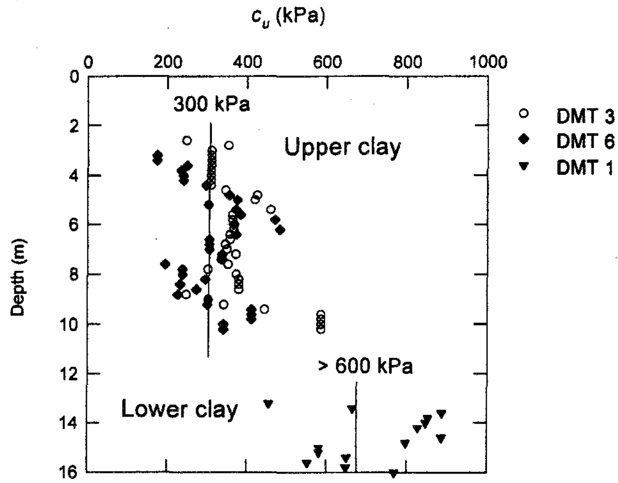

FIG. 14. Shear Strength from DMT at Upper and Lower Tertiary Clay Layers

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 two DMT boreholes are presented in Fig. 11 and in Fig. 12. The upper clay layer (Fig. 11) 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 $K_D \cong 2$, the clay is normally consolidated. The plot of K_D in Fig. 11 indicates that the clay is strongly OC at the top, and tends to a normally consolidated (NC) state at the bottom.

Data for the lower Tertiary clay are plotted in Fig. 12. The undrained strength is very high, ranging from 500 to 800 kPa; M ranges from 200 to 300 MPa, and K_D is also very high at the top, ranging from 20 to 50, but it decreases with depth. This is an indication that this clay is highly overconsolidated at the top, but tends to NC at the bottom.

Marchetti et al. (1994) unpublished article, 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, remolding, and reconsolidation. This may explain the drop in K_D at 9 m depth in Fig. 11 and at 12–13 m depth in Fig. 12. The drops in M values at 7 and 8 m depths in Fig. 11 can be explained by corresponding changes in I_D values.

The stress history indicated by DMT profiles in both clays 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 Fig. 13. 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 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.

Fig. 14 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 gives twice that value.

GROUND-WATER LEVEL IN 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,

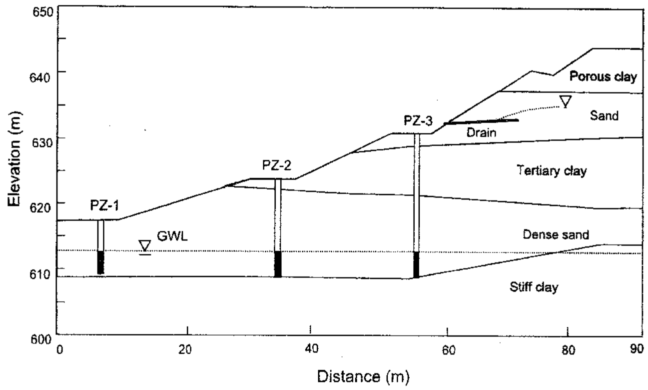

FIG. 15. Ground Water Level in Upper and Lower Sand Layers

on the suspicion of perched water over the upper clay, a series of subhorizontal drains 12 m long and 50 mm in diameter were installed in 75-mm boreholes at 5-m spacing (Fig. 15). As water 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 ground-water level in this layer was investigated by using six Casagrande piezometers split into two instrumented sections. The layout of one section is plotted in Fig. 15. 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 Fig. 4. The major one, described earlier in this paper (Fig. 4), 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.

Shallow failures owing to slaking of the Tertiary clay were also analyzed. In fact, during reconstruction works, a shallow slip took place in the greyish-green upper clay layer. Field observations indicated the slip surface was very shallow and could be a consequence of slaking, which took place at the clay surface. Therefore, this slip can be back analyzed to assess the effect of decay on the clay strength.

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. Soil Parameters for Stability Analyses

Soil layer (1)	Cohesion (kPa) (2)	Friction angle (degrees) (3)	Unit weight (kN/m³) (4)	Assumed behavior (5)	Pore pressures (6)
Porous clay	20	26	17	Drained	None
Upper sand	0	30	18	Drained	1 m below top
Upper tertiary clay	—	—	18	Undrained or drained	—
Lower dense sand	0	30	18	Drained	At elevations of 613 m
Lower very stiff clay	600	0		Undrained	None

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 behavior 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 Intact Clay

Results of the back analyses of the major failure are given in Table 4 and in Fig. 16.

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 analyze 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; $\phi_u = 25°$; see Fig. 7) 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.

TABLE 4. Results of Back Analyses of Major Failure

Strength assumption (1)	c_u or c' (kPa) (2)	ϕ_u or ϕ' (degrees) (3)	Pore pressures (kPa) (4)	FS (5)
UU	55	0	nil, undrained	1.044
UU	0	25	nil, undrained	0.977
UU	5	25	nil, undrained	1.081
UU	10	25	nil, undrained	1.136
CIU	32	19	nil, drained	1.261
CID	55	18	nil, drained	1.383

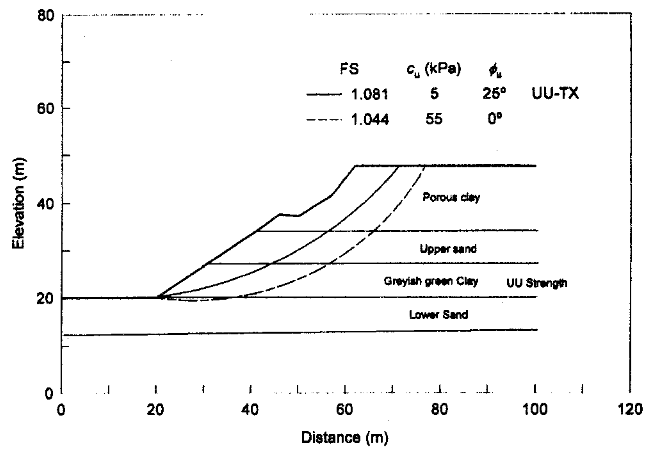

FIG. 16. Back Analysis of Major Failure

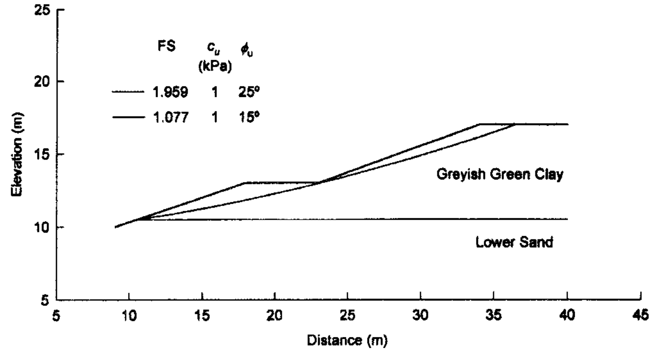

FIG. 17. Back Analysis of Shallow Failure in Greyish Green Tertiary Clay

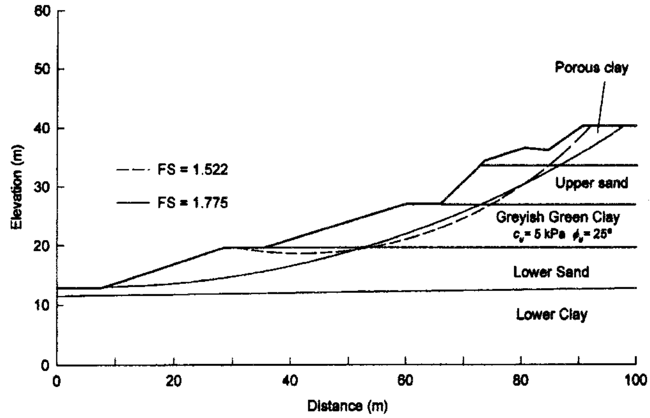

FIG. 18. Stability Analysis for Final Design

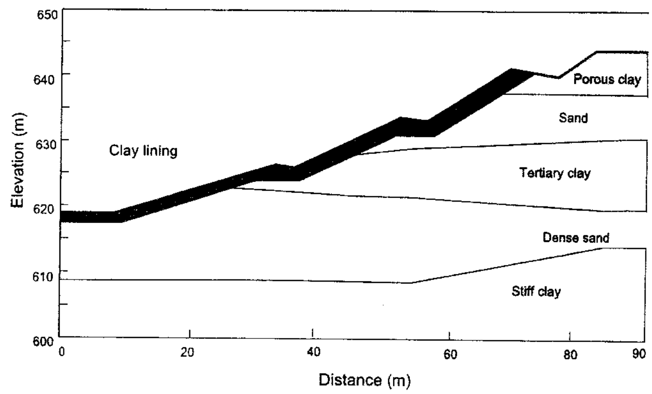

FIG. 19. Final Cross Section Design

Results in Table 4 demonstrate that UU triaxial strength with c_u = 5 kPa and ϕ_u = 25° leads to a factor of safety (FS) close to one at failure. On the other hand, keeping ϕ_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.

Strength of Slaked Clay

The strength of the slaked clay was back analyzed through the shallow failure shown in Fig. 17. It consisted of keeping c_u very low (1 kPa) and reducing the value of ϕ_u until the resulting FS was near to one. The resulting ϕ_u is 15°. The resulting slip surface was very shallow and matched field observations. Alternatively, attempts to decrease ϕ_u and increase c_u led to a deeper failure surface, which clearly did not agree with field observations.

The results of these back analyses can only be regarded as preliminary and deserve further consideration and additional laboratory testing to quantify the effect of slaking.

Final Design

The final design consisted of flattening the slopes, adding 4-m-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 Fig. 18. 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 Fig. 19.

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 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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APPENDIX. REFERENCES

Lunne, T., Lacasse, S., and Rad, N. S. (1989). "SPT, CPT, pressuremeter testing and recent developments on in situ testing of soils, part I: all tests except SPT." *Proc., XII ICSMFE*, Session 2, Vol. 4, 2339–2403.

Marchetti, S. (1980). "In situ tests by flat dilatometer." *J. Geotech. Engrg. Div.*, 106(3), 299–321.

Ortigao, J. A. R. (1994). "Dilatometer in Brasflia porous clay." *Proc., 7th Int. Symp. of Engrg. Geol.*, Oliveira et al., eds., A. A. Balkema, Rotterdam, The Netherlands.

Ortigao, J. A. R., Alves, L. S., Brandi, V. R., and Far, J. (1995). "*Rstabl*: a program for stability analysis of reinforced soil slopes." *Proc., Symp. on Geosynthetics, Geossintéticos 95*, 363–371.

Ortigao, J. A. R., Cunha, R. P., and Alves, L. S. (1996). "In situ tests in Brasflia porous clay." *Can. Geotech. J.*, Ottawa, Canada, 33, 189–198.

Ortigao, J. A. R., Kochen, R., Farias, M. M., and Assis, A. A. (1996). "Tunnelling in Brasilia porous clay." *Can. Geotech. J.*, 33, (Aug.), 565–573.