Laboratory tests and applied geophysical investigations in collapsible soil horizon definition

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Abstract: In order to establish different horizons of soil profiles and their different behaviour under wetting and application of compression/tension to collapsible behaviour identification, three soil profiles were investigated in Ilha Solteira, Brazil. Three soil profiles were identified in Ilha Solteira urban area using terrain evaluation techniques and simple laboratory tests (characterization tests). Looking for techniques of collapsible soil identification in a tropical environment that provide rapid and reliable results, electrical and GRP geophysical surveys were conducted, and their results in terms of collapsible soil horizon identification were checked using in situ (CPT and SPT) investigations and laboratory (confined compression) tests. Geophysical responses allowed soil horizon discrimination, and in situ and laboratory test results indicated collapsible behaviour in two of the studied profiles and permitted the identification of different intensities of collapse in two horizons of each soil profile. The results indicated a new approach for urban planning in Ilha Solteira, based on soil behaviour and different engineering techniques in order to construct buildings and use different parts of urban area for distinct kinds of human activities.

Résumé: Pour établir des horizons différents de profils du sol et leur comportement différent sous mouiller et application de compression/tension à l'identification du comportement pliante, trois profils du sol ont été enquêtés sur dans Ilha Solteira, Brésil. Trois profils du sol ont été identifiés dans Ilha Solteira région urbaine qui utilise des techniques de l'évaluation du terrain et des essais de laboratoire simples (la caractérisation teste). Chercher des techniques d'identification du sol pliante dans environnement tropique qui fournit des résultats plus rapides, électrique et GRP que les études géophysiques ont été menées, et leurs résultats quant à identification de l'horizon du sol pliante ont été vérifiés utiliser dans situ (CPT et SPT) enquêtes et laboratoire (a restreint la compression) épreuves. Les réponses géophysiques ont autorisé la discrimination de l'horizon du sol, et dans situ et résultats de l'essai de laboratoire le comportement pliant a indiqué en deux des profils étudiés et a autorisé l'identification d'intensités différentes de chute subite dans deux horizons de chaque profil du sol. Les résultats ont indiqué une nouvelle approche pour urbanisme dans Ilha Solteira, basé sur comportement du sol et techniques de l'ingénieur différentes pour construire des bâtiments et usage parties différentes de région urbaine pour genres distincts d'activités humaines.

Keywords: collapse, soil mechanics, in situ tests, laboratory tests, geophysics, environmental urban geotechnics.

INTRODUCTION

Soil collapse can be described as rapid structure soil deformations caused by one or more of the following factors: changes in tension state, electromagnetic equilibrium, or cementing characteristics. Collapse-prone soils tend to possess certain characteristics that predispose the phenomenon, for example: a porous structure, a partial degree of saturation and a meta stable structure.

This kind of soil is very common in Brazil, mainly in São Paulo State, where it represents about 70% of the territory. In Ilha Solteira these soils occur in almost all urban areas and associated soil collapse is responsible for much damage in several public and private builds, with resulting large material losses. In this situation, the capability to identify the occurrence of these soils is important to urban planning in order to define priority areas for development and the technical criteria applicable to these areas.

Identification of collapsible soil behaviour traditionally requires expensive and time-consuming laboratory testing programmes which are often economically impractical for small cities in developing countries like Brazil. One way to address this problem could be the use of cheap and easily deployed survey techniques such as geophysical methods associated with rapid *in situ* or laboratory tests. With this in mind, the current work was undertaken in order to establish relationships between geophysical surveys (electrical and GPR methods) and *in situ* and laboratory tests in order to develop a mechanism for identifying collapsible soil profiles.

STUDIED SOIL PROFILES

General Characteristics

Lollo (1998) identifies three different soil profiles in Ilha Solteira urban area. These soil profiles are related to three terrain elements whose description is presented in Table 1.

Table 1. Description of terrain elements in the Ilha Solteira urban area (Rodrigues, 2003)

Profile	Landform	Soil	Occurrence
A	Flat top and convex slopes.	SC – soil thickness greater than 20m.	Southeast, northeast and centre of the area (2,5 km^2)
B	Concave bottom slopes.	SC – soil thickness less than 13m.	South and centre of the area (2,0 km^2)
C	Straight slopes.	SM – less than 7m thickness.	West of the area (0,4 km^2)

Preliminary laboratory tests indicate that each soil profile consists of two intervals thus divided: Soil A – upper interval 0-8m deep (A1), lower interval 8-20m deep (A2); Soil B – upper interval 0-4m deep (B1), lower interval 4-13m deep (B2); Soil C – upper interval 0-2m deep (C1), lower interval 2-7m deep (C2). The physical indices of these six soil profile intervals are presented in Table 2 in terms of average values.

Table 2. Terrain elements description (Oliveira, 2002)

Soil	ρ (g/cm^3)	ρ_d (g/cm^3)	ρ_s (g/cm^3)	w (%)	S_r (%)	e	LL (%)	LP (%)	IP (%)
A1	1.65	1.52	2.67	10.2	30.2	0.80	24.2	15.3	6.9
A2	1.72	1.56	2.71	12.2	45.4	0.72	27.5	18.7	8.8
B1	1.62	1.52	2.64	6.3	25.8	0.74	25.2	17.2	8.0
B2	1.69	1.55	2.67	9.1	33.9	0.70	25.2	17.5	7.7
C1	1.55	1.47	2.69	5.8	22.5	0.85	27.9	15.7	12.2
C2	1.68	1.56	2.72	8.8	32.8	0.75	27.9	15.0	12.9

ρ – natural density; ρ_d – dry density; ρ_s – grain density; w – wet; S_r – degree of saturation; e – void ratio; LL – liquid limit; LP – plastic limit; IP – plasticity index.

Laboratory Tests

In order to characterize collapsible behaviour twelve inspection wells were excavated to ten meters depth with undisturbed soil samples collected at each metre. These sample were tested in laboratory, firstly using rapid empirical methods to determine collapsible behaviour and, secondly, using confined compression tests.

Oliveira (2002) tested and assessed the rapid empirical methods described by Denisov (1951), Priklonskij (1952), Gibbs & Bara (1962), and the Soviet Building Code (1962). The results obtained with these techniques showed inconclusive data, and did not enable to soil collapsible behaviour be predicted or defined with confidence.

Rodrigues & Lollo (2004) susbsequently performed double confined compression tests (under natural moisture content and fully saturated conditions) on the same samples (collected at each meter in inspection wells) in order to better characterize collapsible horizons in the soil profiles. The results obtained enabled collapsible behaviour to be defined more accurately and tended to confirm the soil horizon divisions observed in preliminary surveys.

The three soil profiles show characteristic behaviour for each defined horizon, permitting different classes of collapsible behaviour to be defined, as shown in Figures 1 to 6.

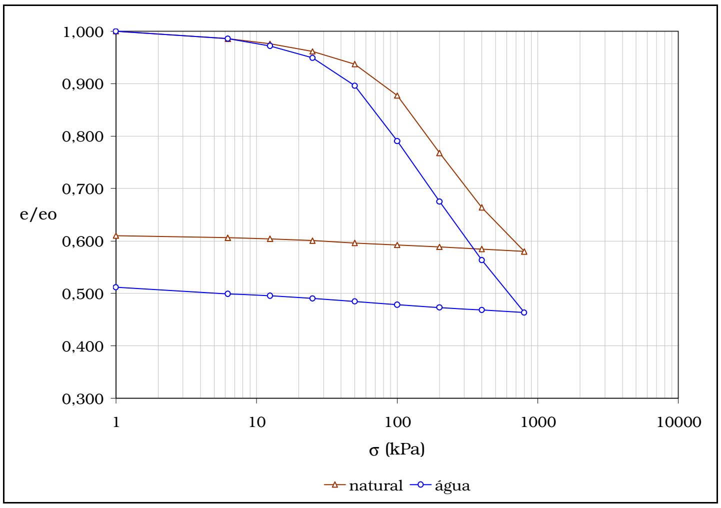

Figure 1. Double Confined Compression Test – A1 horizon (Rodrigues & Lollo, 2004)

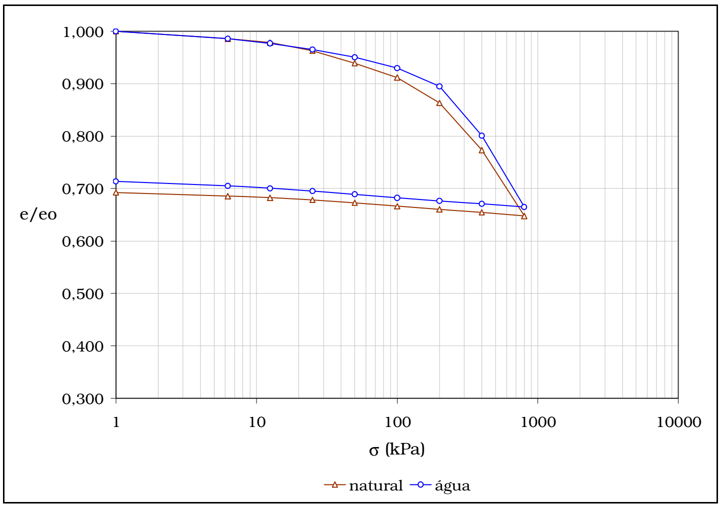

Figure 2. Double Confined Compression Test – A2 horizon (Rodrigues & Lollo, 2004)

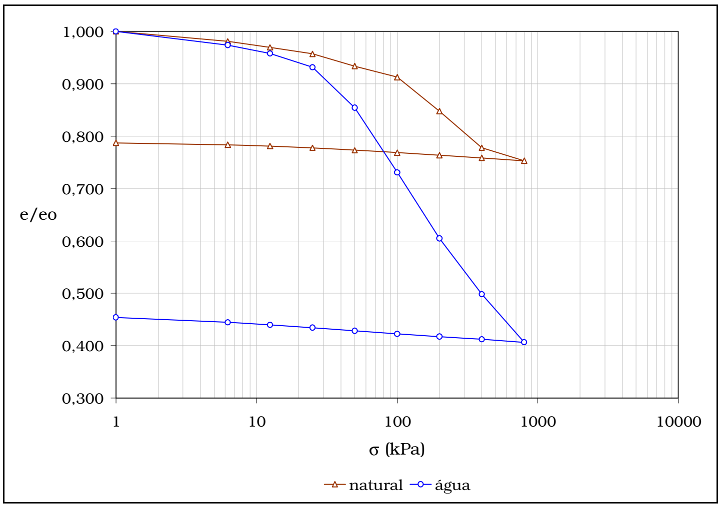

Figure 3. Double Confined Compression Test – B1 horizon (Rodrigues & Lollo, 2004)

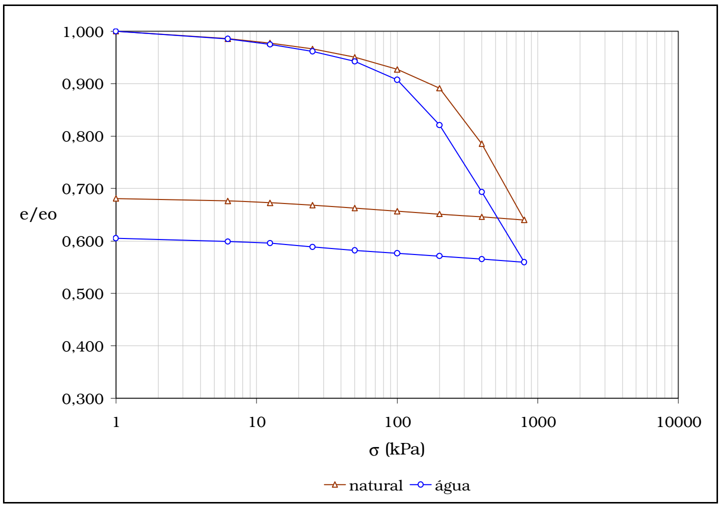

Figure 4. Double Confined Compression Test – B2 horizon (Rodrigues & Lollo, 2004)

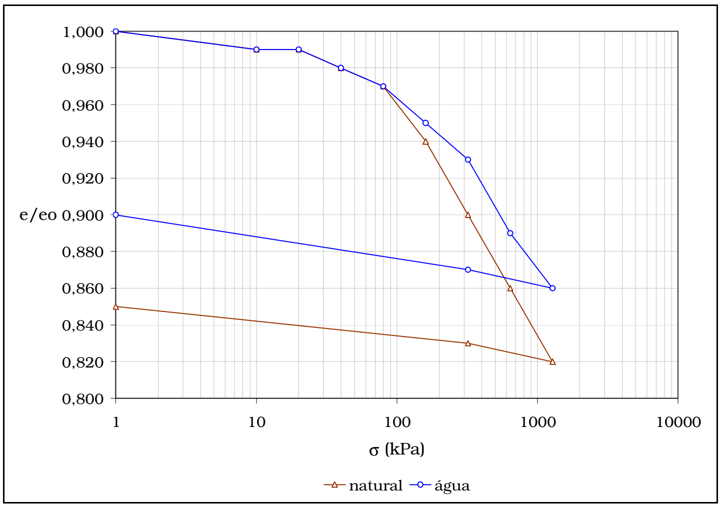

Figure 5. Double Confined Compression Test – C1 horizon (Rodrigues & Lollo, 2004)

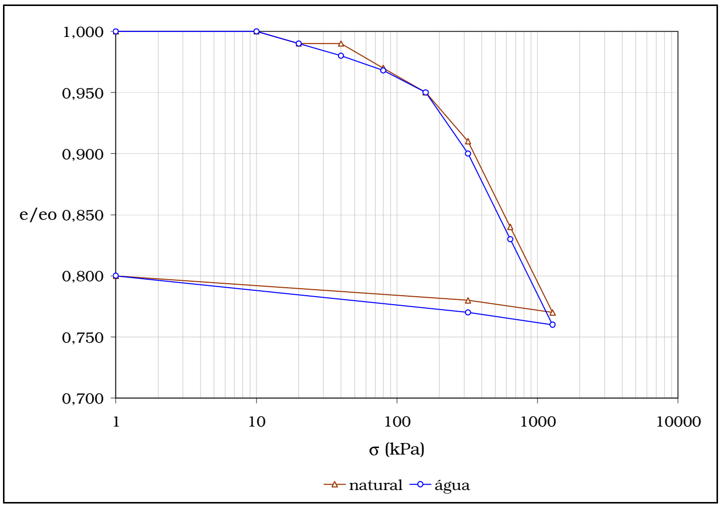

Figure 6. Double Confined Compression Test – C2 horizon (Rodrigues & Lollo, 2004)

The results show that soil profile C (C1 – upper and C2 – lower intervals) does not undergo additional deformations (collapsible behaviour) due to wetting, and as such these soil horizons were not considered further in the present study.

IN SITU TESTS

To establish the relationship between laboratory behaviour determined from the confined compressing tests and *in situ* behaviour, SPT test data were obtained for typical sections of soil profiles A and B. The SPT values show a soil horizon definition that confirms the laboratory test data, the SPT logs being illustrated in Figures 7 and 8.

For Soil Profile A, SPT results show a lower density upper section to 8m depth, with N values lower than seven, corresponding to upper interval A1. This range of SPT values, in Ilha Solteira region, usually defines the collapsible soil horizon. At depths greater than 8m, the SPT N values range from equal to or greater than seven, increasing with depth until penetration refusal is met at 17m, where the soil profile consists of a stony layer of 10mm diameter quartz pebbles.

For Soil Profile B, the SPT results show a less thick lower density upper horizon (B1), with N values less than seven, to around 5m depth, followed by a stony horizon consisting of 20mm diameter quartz pebbles that results in non-penetration of the SPT sampler. The lower interval of this profile (B2) is characterised by a rapid increase in SPT N values to around twenty immediately under the stone line.

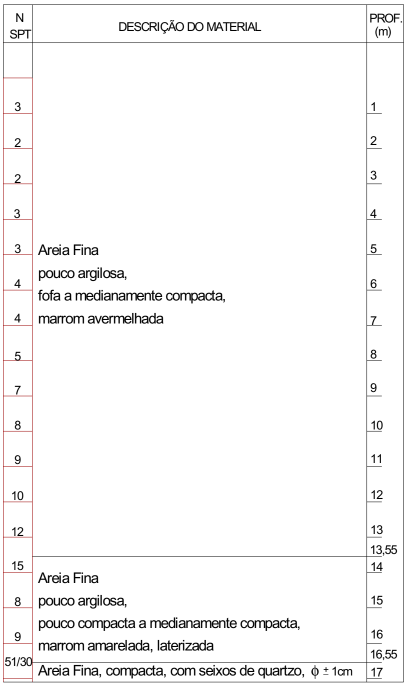

Figure 7. SPT test data for Soil A profile (Lollo, Elis & Prado, 2003)

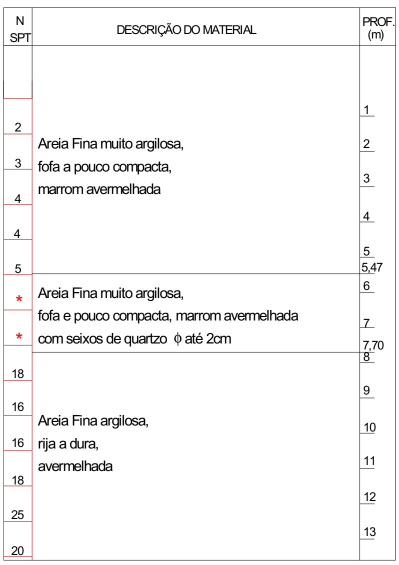

Figure 8. SPT test data for Soil B profile (Lollo, Elis & Prado, 2003)

GEOPHYSICAL SURVEY

Geophysical survey methods included the use of electrical and Ground Probing Radar (GPR) techniques. Of the electrical methods, the most interesting results were obtained with vertical electrical sounding and electrical profiling. The GPR results were found to be very much affected by interference and this technique could not be successfully used in this study.

Eight vertical electrical explorations were undertaken at the same locations where the inspection wells and SPT tests were acquired. The obtained results are shown in Figures 9 and 10.

Four electrical profiling surveys were undertaken at locations representing typical soil profiles, where inspection wells and SPT tests were sited, and where there was no building development that constrained the survey. The electrical profiling lines are presented in Figures 11 to 14.

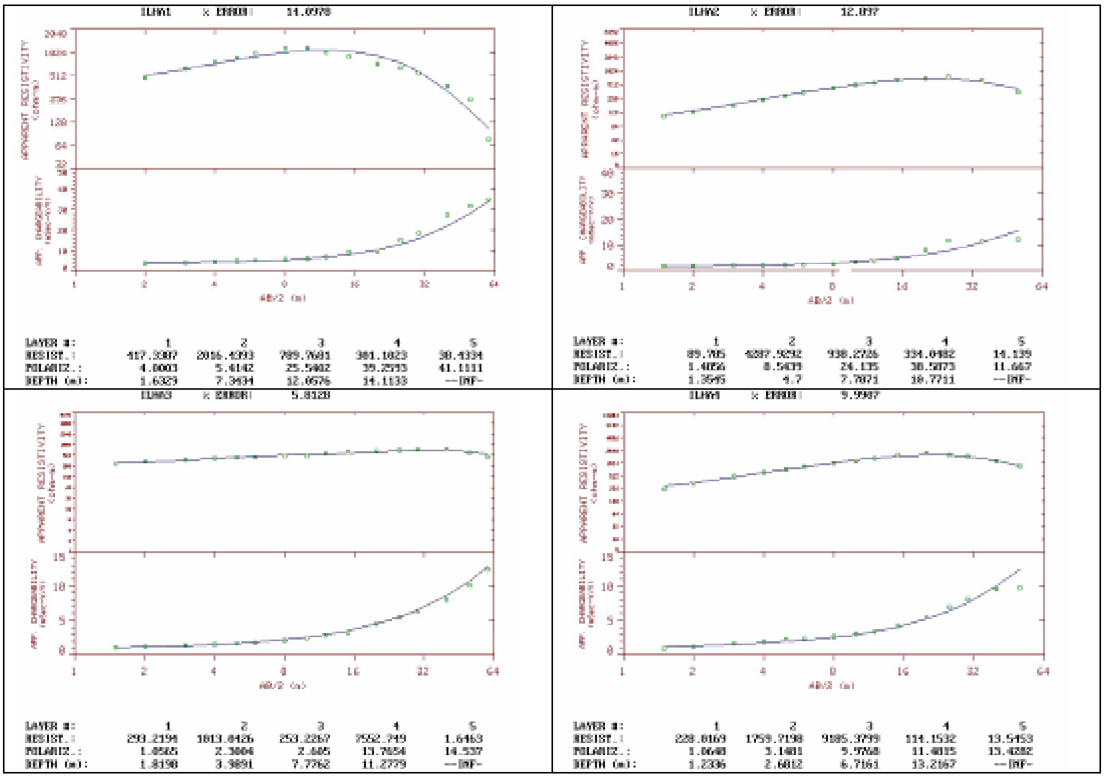

Figure 9. Vertical electrical soundings number 1 to 4 (Lollo, Elis & Prado, 2003)

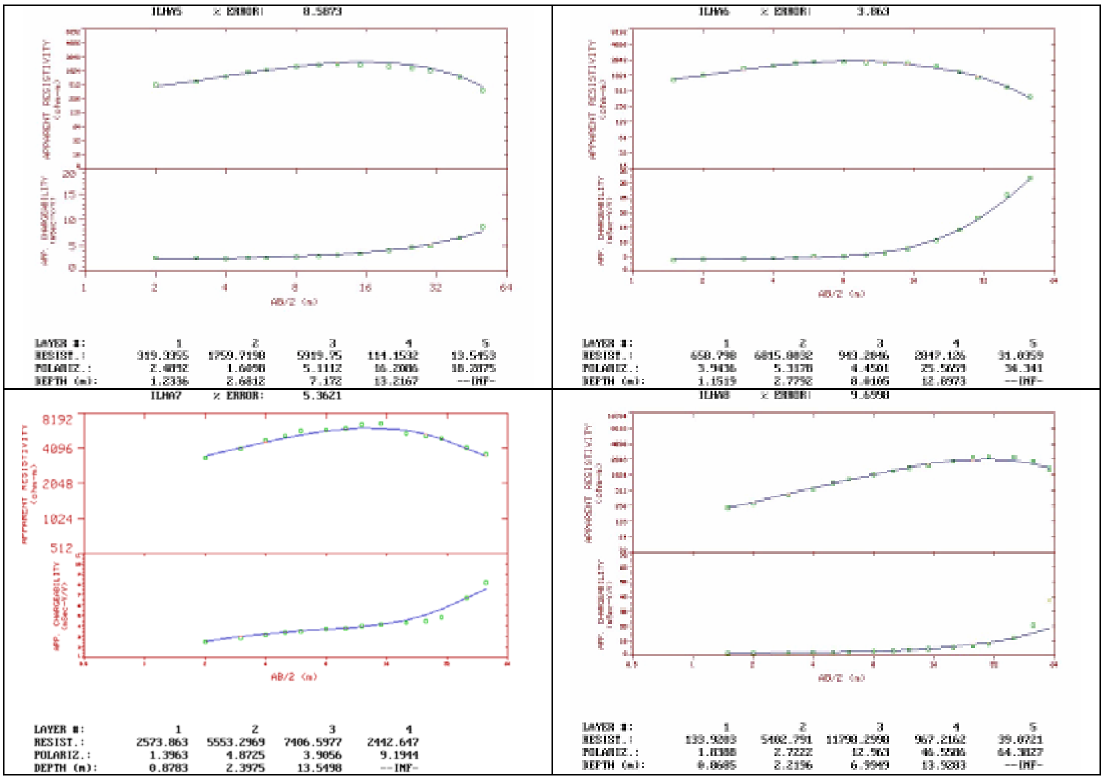

Figure 10. Vertical electrical soundings number 5 to 8 (Lollo, Elis & Prado, 2003)

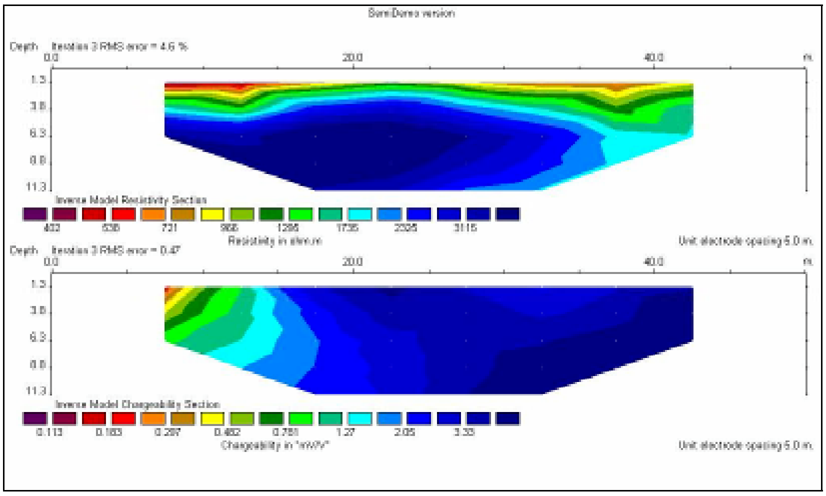

Figure 11. C1 electrical profiling line (Lollo, Elis & Prado, 2003)

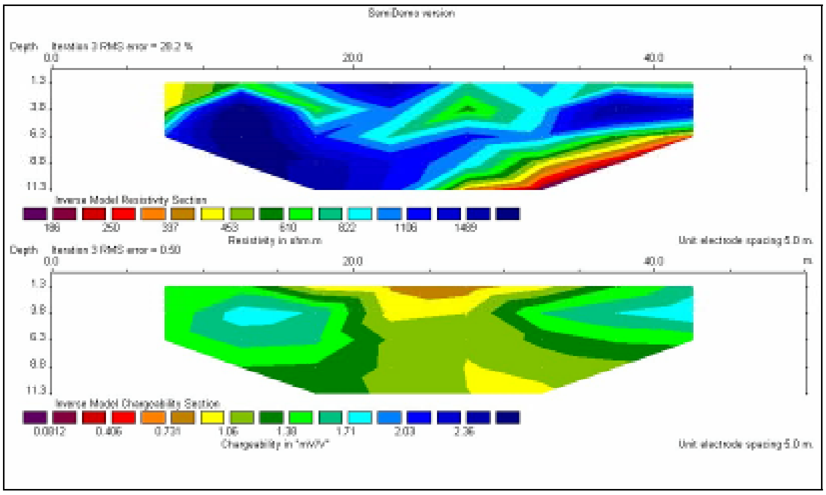

Figure 12. C2 electrical profiling line (Lollo, Elis & Prado, 2003)

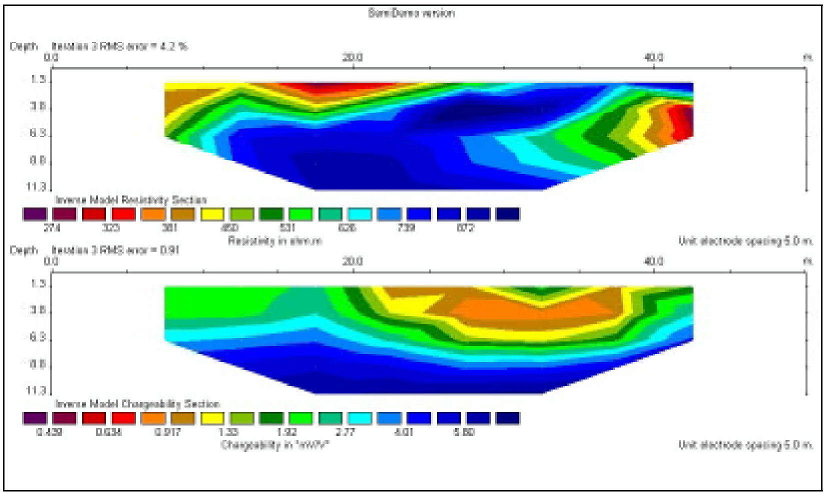

Figure 13. C3 electrical profiling line (Lollo, Elis & Prado, 2003)

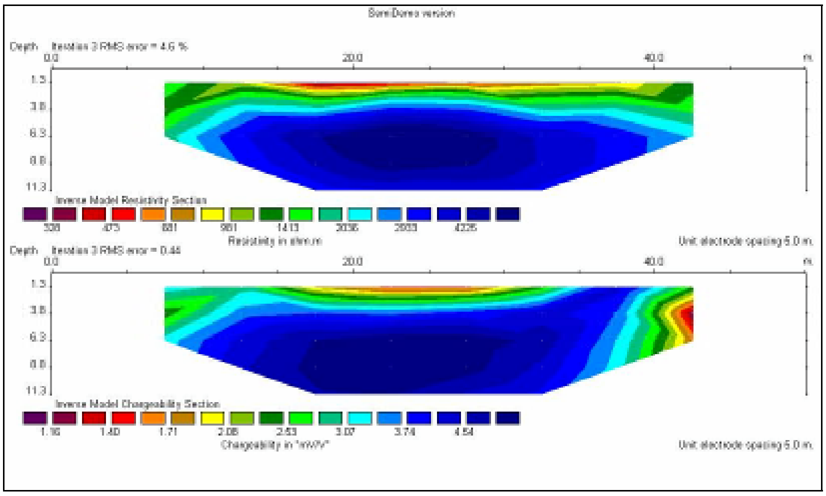

Figure 14. C4 electrical profiling line (Lollo, Elis & Prado, 2003)

GEOPHYSICAL RESULTS AND COLLAPSIBLE SOIL BEHAVIOUR

Vertical Electrical Sounding (VES)

Vertical electrical soundings show geo-electrical models that permitted definition of the soil horizons and saturated zone. The high resistivity values in all VES are indicative of the sandy nature of the studied materials.

As this pattern is unique for the upper horizons of the two soil profiles considered, and the most common type of foundation used in Ilha Solteira (piles) rarely exceeds 4m deep, the following analysis is valid for all the profiles of collapsible soils occurring in the area.

Considering the soil information from laboratory and in situ tests, a relationship can be observed between zones with low density/compactness and high porosity, with lower SPT values, at deeps from 1-2m to 6-8m. These horizons represent those soil zones with collapsible behaviour.

Another significant result is that chargeability for these collapsible soil horizons shows small to medium values (2.7 to 9.97mV/V), with the lower limit of the horizon marked by a decrease in resistivity and increase in chargeability, possibly related to an increase in wetting.

The limit of the saturated zone exhibits typical values of 13.5 to 39ohm.m for resistivity and 11.7 to 64.1mV/V for chargeability.

Results from the vertical electrical explorations 1 to 3 (Figure 9) indicate that the second horizon yields the higher resistivity values. In vertical electrical explorations 4 to 8 (Figure 9, lower right and Figure 10) very high values of resistivity occur in horizons two and three, indicating collapsible behaviour.

In VES 1 the high resistivity layer (2016ohm.m and 5.4mV/V) occurs between depths of 1.6 to 7.3m, with soil SPT N values of 2 to 3. The layer below shows a significant increase in SPT N value, a resistivity decrease to 789ohm.m and increase in chargeability to 25.5mV/V. These changes can be explained by an increase in wetting and soil lateritization.

This tendency occurs also in VES 2 and 3, with the second layer showing resistivity and chargeability values of 1013 to 4288ohm.m and 2.3 to 8.5mV/V, respectively, for more porous and less wet soil. The third horizon shows resistivity values of 253 to 938ohm.m. Chargeability of this third horizon in VES 3 is lower than VES 1 and 2, indicating less soil laterization.

In VES 3 to 8, the soils with the highest porosity and lowest wetting are represented in horizons 2 and 3, with resistivity values of 1759 to 11798ohm.m and chargeability values from 1.6 to 9.97mV/V. The bed below shows values of resistivity from 114 to 967ohm.m and chargeability from 11.5 to 46.6mV/V. It should be noted that because of anomalously high resistivity values, VES 6 and 7 are not considered in this analysis.

Thus, the overall results indicate that the soil horizons with higher porosity and lower wetting, are characterised by highest resistivity values (more than 2000ohm.m) and small chargeability (always less than 10mV/V). These horizons coincide with collapsible behaviour of the soils identified in laboratory tests.

Electrical Profiling

Electrical profiling surveys, using the same resistivity and chargeability limits used in vertical electrical soundings, enabled variation of the lateral soil horizon to be assessed, particularly the top of the high resistivity layer. However, the base of this layer was not well defined due to limits associated with resolution of the test equipment. Interpreted sections are presented in Figures 11 to 14.

In Line C1 (undertaken in a typical Soil A profile area) the top of a high resistivity layer at around 3.5m depth can be observed. The chargeability section does not show the geometry of this layer with any clarity but, together with the resistivity profile tends to indicate a tendency for potentially collapsible soil horizon to extend to the base of the profile.

Line C2, undertaken in a typical Soil B profile area, shows a more complex pattern of high resistivity horizon, with variations in its thickness and thinning of this layer in the bottom of the profile. Chargeability values vary little and are small across all of the section.

Line C3 results show a complex pattern, as line C2, with significant variations in the high resistivity layer depth and a tendency of thinning of this layer with depth in the profile direction. Chargeability values also show small variations.

In Line C4, the resistivity section indicates a high resistivity, and hence potentially collapsible, soil layer present in virtually all the profile below 4m depth. The subjacent lower layer, identified in VES, isn't evident in the profiling. As in Lines C2 and C3, the chargeability values show no significant variations across the profile section.

Thus, from the results of the current data, the electrical profiling enables identification of the upper limit of high resistivity layers. Its bottom limit was defined only in some sections, and even then rather tentatively.

CONCLUSIONS

The obtained results enable the following conclusions to be made: (1) the geophysical survey enabled confirmation of soil horizons in the studied profiles and aided in the assessment of lateral profile variations; (2) vertical electrical sounding was the most efficient technique for determination of the top and base of the collapsible soil horizons; (3) electrical profiling enabled lateral variations of the high resistivity layers (potential collapsible soil horizons) to be identified; (4) the use of a suite of techniques composed of basic survey, laboratory tests, *in situ* tests and geophysical survey can be effectively and efficiently utilised to characterize collapsible soil behaviour at specific sites; (5)

geophysical survey, using vertical electrical sounding and electrical profiling, can be very useful for preliminary identification of collapsible soil horizons, providing basic information for urban planning.

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