CPTU interpretation for stratigraphic logging: differences between sedimentary and residual soils

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ABSTRACT: An interpretation of piezocone (CPTU) data of a sedimentary soil and two distinct residual soil profiles from Brazil and Portugal are presented. The main objective is to show the differences in the interpretation of these soil types. The interpretation of sedimentary soil allowed for a clear distinction of the layers, their classification and detailing the transitions, which contributed to understanding the soil formation. In the case of residual soil from Portugal, no distinction was found between layers. However, the tropical residual soil from Brazil showed horizons formed by pedogenetic process, with different responses to piezocone penetration and with gradual transitions between the horizons. The CPT-based soil classification chart is not applicable to either of these soils. The ratio G_o/q_c demonstrated to be useful in identifying unusual soil compressibility and to define different classes of weathered soils.

1 INTRODUCTION

The definition of the geotechnical soil profile is fundamental in engineering design. The geotechnical soil characteristics are evaluated based on an understanding of the spatial distribution of the various types of materials in the subsoil, which is obtained by means of pointwise data from several drillings or piezocone profiles and stratigraphic interpretation. This distribution is a function of the history of geological processes that acted in the formation of soils and rocks. In highly homogeneous soils or in regions of sedimentary layers with lateral continuity, this interpretation is done by interlinking similar points and extrapolating test data for the regions situated between them. When there is considerable heterogeneity, which is indicated by very distinct soil characteristics between tests, interpretation becomes more complex.

Soil behavior charts using CPTU data have been very useful for the identification of strata in sedimentary soils. However, it has been recognized that these variables, especially u_2 measurements, cannot always be considered useful to ensure a proper soil classification in unusual geomaterials, currently called *non-textbook* geomaterials, particularly in residual saprolitic and lateritic soils. Since these soil behavior classification charts should rely on at least two independent measurements, in the absence of pore pressure measurements, it has been suggested Schnaid et al (1998) that q_c should be compared with a small strain stiffness, G_o.

2 PIEZOCONE TEST (CPTU)

The piezocone penetration test (CPTU) has an instrumented probe with a 60° apex and 35.7 or 44 mm diameter on the end of a series of rods. The probe is pushed into the ground at a constant rate of 20 mm/sec measuring tip resistance (q_c), friction sleeve stress (f_s), and pore pressure (u). Soil can be classified using specific charts and the best methods combine both tip and sleeve measurements with some type of pore pressure interpretation. Pore pressure measurements cannot always be considered useful to ensure proper soil classification of residual soils, due to loss of saturation. Recent work in problematic soils has led to the recognition that the combination of small strain stiffness (G_o) and cone tip resistance (q_c) can be useful to identify soils with unusual compressibility. The addition of a seismic receiver in the cone allows for down-hole seismic testing during the SCPTU.

3 STUDIED SITES

3.1 *Sedimentary soil site*

The study site is a pier for mineral transport in the city of Caravelas on the southern coast of the state of Bahia, Brazil. Andrade et al. (2003) concluded that the historical evolution and sediment distribution were controlled by sea level fluctuations during the Quaternary period, with influence of sea water currents and coral barriers. Two piezocone tests were carried out to support the pier design. Tip resistance (q_c) and sleeve friction (f_s) were measured and pore-pressure (u_2, that is the sensor situated in the shoulder) was recorded using the piezo element saturated with glycerin.

3.2 *Portuguese residual soil site*

The site is the ISC'2 research site on the campus of the University of Porto, in Portugal (Viana da Fonseca et al 2006). The site has an upper layer of heterogeneous residual saprolitic granite soil of variable thickness, overlaying more or less weathered granite contacting high grade metamorphic rocks (gneisses and migmatites). Nine CPTU tests were carried out at the site and pore pressure (u_2) was recorded using the piezo-element saturated with glycerin. S- and P-wave cross-hole survey on three boreholes allowed the determination of the G_o and calculation of the average G_o/q_c ratio.

3.3 *Brazilian residual soil site*

The research site is located on the campus of the University of Campinas, in the state of São Paulo, Brazil (Cavalcante et al 2007). From 30 to 20 m depth there is an immature saprolite of diabase with many blocks. A mature saprolite with sparse blocks of partially weathered rocks predominates from a depth of 6 to about 20 m. Porous clay predominates above a depth of 6 m up to ground level. Several CPTU tests were carried out at the site and in some tests, pore pressure measurements were taken using a slot filter filled with automotive grease (Mondelli et al 2009). Two seismic cone tests were also carried out, allowing for calculating the G_o/q_c ratio.

4 CPTU TEST RESULTS

4.1 *Sedimentary soil*

Figure 1 presents one piezocone test results for the Caravelas site. A depth of 35.0 m was reached in this test, and its interpretation indicated the existence of seven main layers, from A to F. The test data were interpreted using a conventional CPT-based soil classification chart proposed by Robertson et al. (1986) (Figure 2). The geological setting, which is defined as marine to transitional sediments with a thickness of about 60 m formed by at least two Transgressive-Regressive cycles, is discussed in detail by De Mio & Giacheti (2007). The layers from A to F represent intercalated sand and silt-clay layers, each one with specific characteristics and correlations with paleogeologic units, as indicated in Figures 1 and 2.

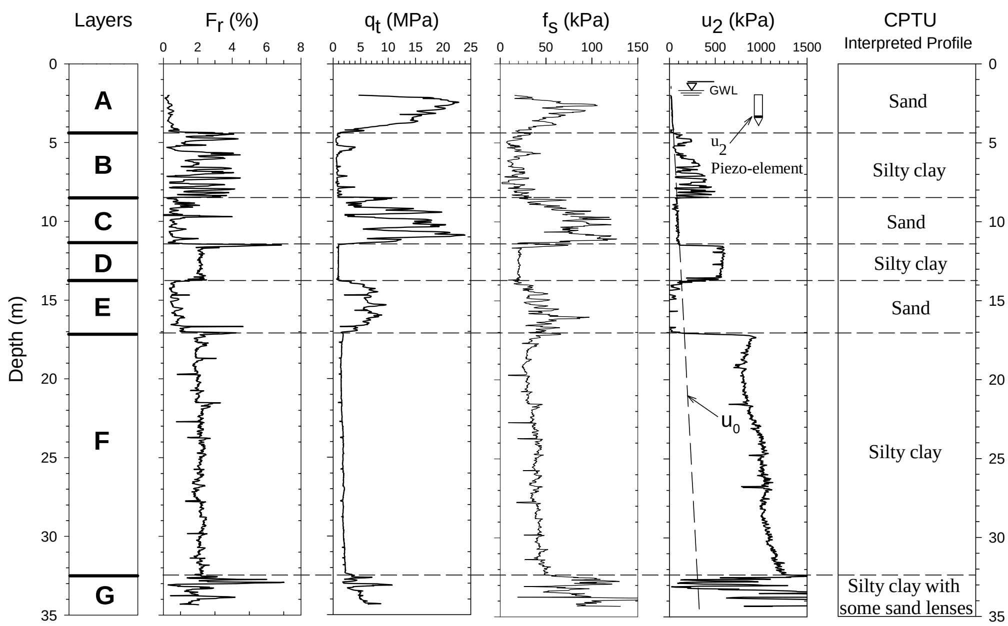

Figure 1: Piezocone test results for sedimentary soil at Caravelas site (De Mio & Giacheti, 2007)

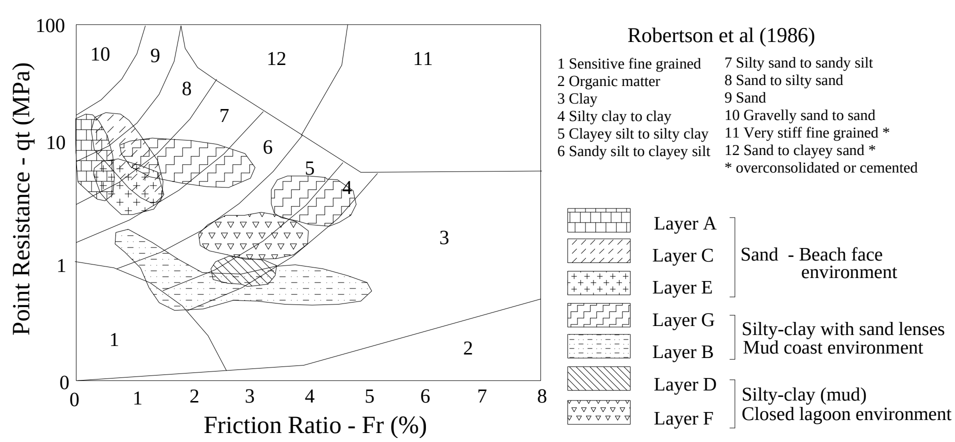

Figure 2: Robertson et al. (1986) chart for sedimentary soils at Caravelas site (De Mio & Giacheti, 2007)

4.2 *Portuguese residual soil*

Figure 3 presents the typical and deepest piezocone test results for the ISC2 experimental research site, including corrected cone resistance (q_t), local lateral friction (f_s), pore-pressure (u_2), friction ratio (F_r) and average G_o/q_c ratio, calculated based on the interpretation of cross-hole and several CPTU test results. **Erro! Fonte de referência não encontrada.** shows Robertson et al. (1986) CPT-based classification charts based on the piezocone testing results, reflecting considerable dispersion in the material type, since this evaluation may be conditioned by unreliable pore-pressure measurements.

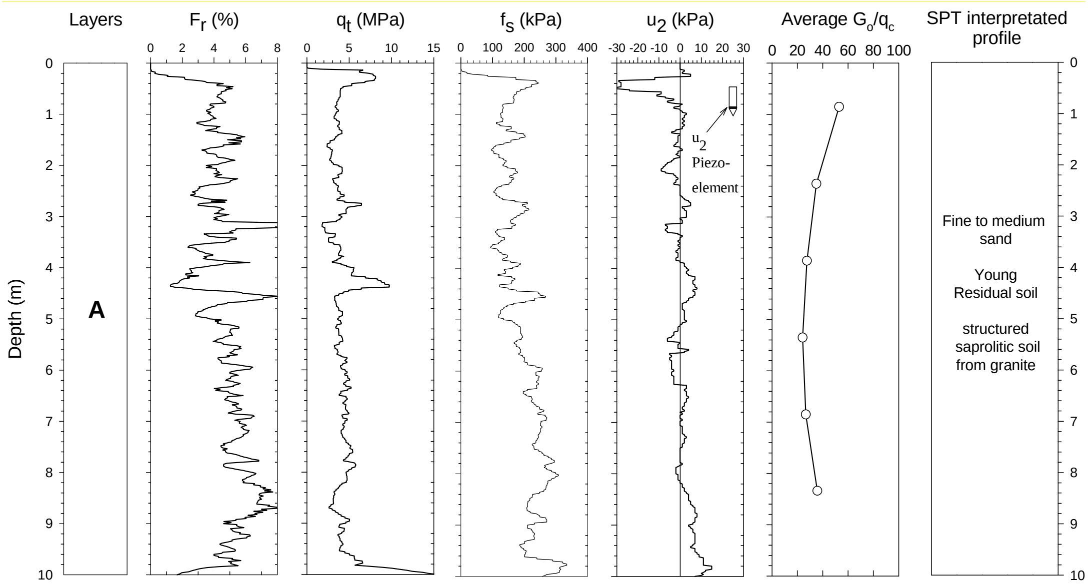

Figure 3: Piezocone test results for Porto ISC2 Site – Portugal residual soil

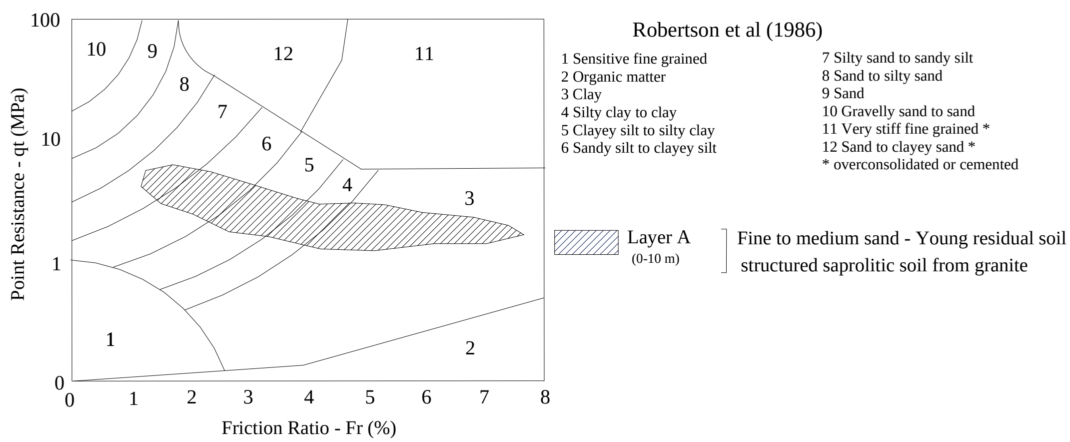

Figure 4: Robertson et al. (1986) chart for residual soil at Porto ISC2 site

The analysis of the test profiles in Figure 3 provides no clear indication of the existence of different strata. Cone tip resistance varies from 4 to 5 MPa, with peaks of up to 10 MPa close to the surface and at 5 m depth. The values of friction ratio varied around 4, with peaks of 2 to 6 between 3 and 6 m of depth. The pore-pressure (u_2) profile also varies close to zero, indicating soils with drained penetration compatible with the classification of fine to medium sand. High average G_o/q_c ratio, varying from 25 to 55, indicates the occurrence of nonconventional soils. The heterogeneities identified in the profile of this piezocone test are repeated in the other tests, albeit at different depths, originated from variations in faulting, composition and degree of weathering of the geomaterials in the profile and indicating the absence of strata with lateral continuity.

4.3 *Brazilian residual soil*

The soil profile interpretation shown in Figure 5 indicates the presence of four main horizons. Horizon A, from 0 to 5.8 m, shows a cone tip resistance varying from 1 to 3 MPa, increasing in depth, with higher resistances in the first 0.5 m. The friction ratio (F_r) shows values varying from 1 to 3%, with a peak of 5% close to 0.5 m. Pore pressure is null because it is situated above the water level. The G_o/q_c ratio indicates values close to 100, which are higher than the values at depth. Horizon B, from 5.8 to 13.5 m, shows a cone tip resistance of 2 to 4 MPa which tends to increase with depth; the friction ratio indicates values close to 7%; pore-pressure shows increasing values starting from the water level at 10 m; and the G_o/q_c ratio shows values varying from 60 to 50. Horizon C, from 13.5 to 19.5 m, shows cone tip resistance of 3 to 4 MPa; friction ratio between 3 and 4% with peaks up to 6%; pore-pressure between 0.8 and 1.4 MPa, increasing with depth; and a G_o/q_c ratio close to 40. Horizon D, from 19.5 m to the end of the profile, shows cone tip resistance of 3 to 5% with peak resistance above 10 MPa close to 20 m and peaks of 6 to 8 MPa at depths of 23 and 24 m; and a highly variable friction ratio between 6 and 10%, with sharp drops at 20 and 24 m of depth.

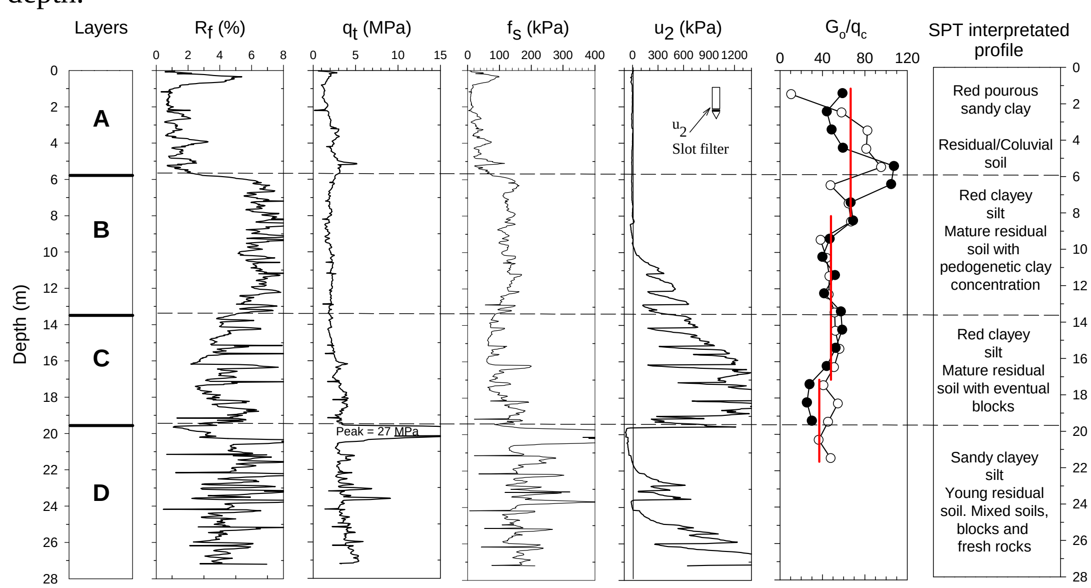

Figure 5: Piezocone test results for residual soils at the Campinas - Brazil site and interpretation of the main layers

Horizon A represents the portion of the profile subjected to leaching processes (eluviation) with formation of Fe and Al oxides, resulting in particle cementations and porous soil formations, evidenced by the higher G_o/q_c ratio than in the deep horizons. Horizon B, and to a lesser extent horizon C, may represent portions of concentration of clayey materials, indicated by the high friction ratio which tends to decrease in depth. Pore-pressure with a slot filter provides records starting from the position of the water level, indicating more clayey soils with intense generation of pore-pressure. In contrast, horizon D shows the presence of moderately to highly altered soil, with the presence of weathered or slightly weathered blocks, indicated by peaks of cone tip resistance and sharp drops in recorded pore-pressure.

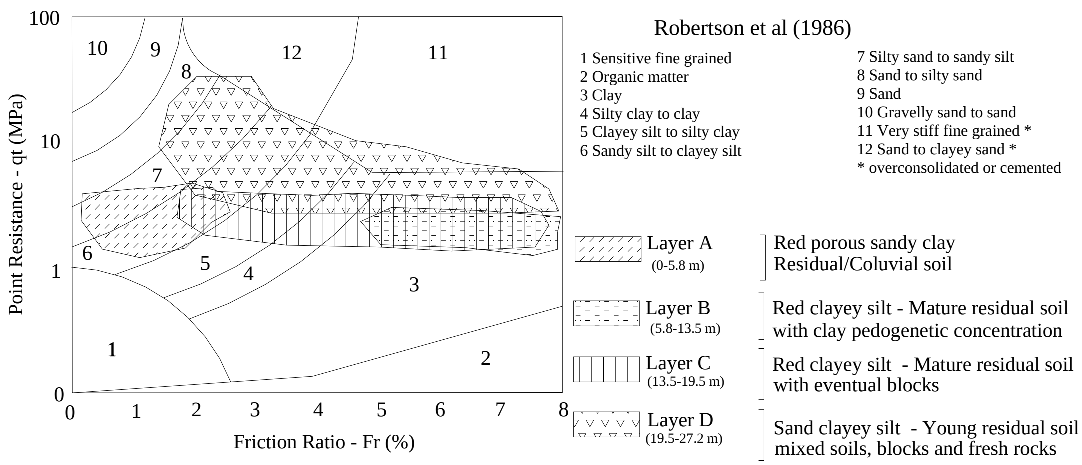

Figure 6: Robertson et al. (1986) chart for residual soils at the Campinas - Brazil site soil distribution

5 DISCUSSION

5.1 *Identification of transition surfaces*

The result of the piezocone test in sedimentary soil (Figure 1) shows transition surfaces inside the sediments marked in the three sensors (q_t, f_s and u), indicating a contrast of properties between silty/clayey layers and sandy layers, with high sensitivity in their identification of up to centimetric dimensions. The identification of transition surfaces in unconsolidated materials developed by tropical weathering is more complex. This complexity stems from the superposition of processes during natural weathering of rock masses, which is mostly induced by the migration of water along relic structures inherited from rock. The weathering alteration tends to become more intense and deeper along faults and fractures and in minerals that are more susceptible to chemical evolution.

In the piezocone test profile of young residual soil from Portugal (Figure 3), transition surfaces are not identified inside the soil mass. The variations in the test result are erratic and do not define horizons with lateral continuity. This is typical of saprolitic masses, where secondary processes of weathering have not occurred,

The piezocone test profile of residual soil from Brazil (Figure 5) shows different strata, interpreted as the product of tropical pedogenetic evolution, which, because they are repeated in the other tests, suggest the existence of strata with lateral continuity. However, the interpretation of the spatial distribution of materials should be done cautiously, considering the geological history and the possibility of sharp variations as a function of structures inherited from fresh rock.

5.2 *Soil Classification*

In the quaternary sediments studied here and represented in the classification chart (Figure 2), variations in the constitution, thickness, extent, and contact relations between layers depend on the environments and the sedimentation agents, as well as the energy involved in the processes. Fine sediments (clays and silts) are concentrated in environments with little energy, such as closed bays, while sandy sediments predominate in environments with greater energy, such as beaches and fluvial environments. In some transitional environments, such as plains and tidal canals, fine intercalations of sandy and silty/clayey materials may be formed as a function of the magnitudes and consequent tidal currents. Nevertheless, the geotechnical characteristics of the sediments are not linked solely to the constitution of sediments and, in several cases, the geotechnical behavior is associated with the over consolidation ratio.

The residual soils of Portugal were formed in temperate climate conditions where the weathering process is less intense than that of tropical soils. Transformations of minerals from fresh rock into micas and clays lead to the reduction of interparticle resistance and decomposition of rock. Fresh granitic rock leads to the formation of predominantly fine to medium sandy soils, which is not in agreement with the classification chart (Figure 4). The layer concept is applied extensively to all the soils studied in engineering, but this concept is faulty in residual soils. Pedogenetic tropical weathering processes are not recorded in these soils due to temperate climate condition, as indicated in Figures 3 and 4.

The profile depicted in Figure 6 is situated over diabase, which can be considered igneous rock of high compositional homogeneity. Thus, the rocky substrate at this site is interpreted as consisting of a single rock type with diverse fractures, which should control alteration fronts. The layer concept is therefore also not applicable and the correlations among tests situated in different portions of the soil mass are limited due to the great variability resulting from tropical weathering. However, the pedogenetic processes of leaching and concentration of clays may lead to the formation of more superficial horizons with lateral continuity, with characteristic responses to the piezocone test (Figure 5), which, when interpreted from the standpoint of geological history, indicate lateral continuity of some of the more superficial strata. In the classification chart (Figure 6), the different units identified in the profile are well differentiated, especially horizons A and B, with typical positions in the classification chart.

6 CONCLUSIONS

The stratigraphic logging and soil classification based on CPTU tests requires knowledge about the geological history and soil genesis to allow for a proper interpretation. It is also important to point out that CPTU tests capture the behavior of the soils as opposed to just a classification based on grain size distribution, especially for residual soils.

In the sedimentary soils of this study, the test results indicate a sharp transition between layers, the degree of granulometric homogeneity of the materials associated with the environment and sedimentation agent, and a clear differentiation in the units of the soil classification chart. In these soils, the water level is usually close to the surface and recording the pore-pressure profile is crucial to interpretations. Interpretation of these soils follows stratigraphic and sedimentological criteria that validate the extensive use of the concept of layers with lateral continuity.

In the young residual soil of the northern coastal region of Portugal, the result of the piezocone test does not clearly indicate the existence of repetitive differences in the various tests along the area. The variations in tip resistance and friction ratio are related to the erratic heterogeneities of the original rock in terms of composition, fracturing and degree of alteration. In the CPT-based soil classification chart, the distribution of points defines a single region and the G_o/q_c ratio indicates the occurrence of nonconventional soils.

In the mature residual soil of the Campinas region, the process of tropical weathering is highly developed, but marked ferrous concretions do not occur. The result of the piezocone test highlights the superficial horizon of porous soil and the horizon of pedogenetic concentration of clay. The transitions between these strata are well marked in the q_t, Fr, and G_o/q_c profile and the strata are individualized in the CPT-based soil classification chart. In residual soils, the use of the concept of layers with lateral continuity should be restricted, but in situations where pedogenetic processes have been very intense, the occurrence of strata with lateral continuity of geotechnical properties is expected, especially in the more superficial horizons (A and B horizons).

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