CPT Regional Report for South America

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ABSTRACT Although the standard penetration test (SPT) is the dominant in-situ test for soil investigation in South America, site characterization is often complemented by other in situ and laboratory tests. The use of the CPT has gradually increased, particularly in Brazil, both in research activities and engineering practice. In soft soils construction, the piezocone is now established as a routine site investigation tool in major infra-structure design projects. Experience gained in clay deposits encouraged the use of the CPT in other applications comprising very soft organic peat, intermediate permeability silty soils, tailing deposits, some highly weathered residual soils, among others. Cone penetration tests are carried out by specialist site investigation contractors that are located in the main towns, which implies on long distance transportation of equipments across the country.

Systematic research activities at Brazilian universities have been given important contribution for the development and improvement of Brazilian standards and practice. Prediction of ground profiling and assessment of design parameters are the most common application of CPTs in Brazil. Considerable increase in the use of the CPT is expected in the near future as a result of the economical growth in the Region.

1 INTRODUCTION

The requirements of a geotechnical site characterization programme are a function of the nature and extension of the project, local ground conditions and risks associated. It is also recommended to give attention to the construction conditions to meet the main goals of determining: geological and hydro geological conditions, geotechnical parameters and geo-environmental issues when indicated.

South America has one of the most unbalanced distributions of resources of all regions in the world and in this context it is difficult to produce an overview of the situation on the continent as a whole. Very often there are reports of small contractors operating regionally which we were unable to identify, so a precise account of the continent experience was not possible and substantial uncertainty inevitably exists. Despite these uncertainties an attempt is made to identify local site investigation practices. Brazil is the country where the most significant CPT experiences in the continent take place, a region exhibiting variable geological formations, encompassing sedimentary costal deposits and vast hilly weathered tropical soil profiles. Marine and alluvial costal deposits spread along dense populated areas are suitable for CPT based site investigation, in particular the soft clay deposits where the piezocone is now established as a routine site investigation tool in major infra-structure design projects. Experience gained in clay deposits encouraged the use of the CPT in other applications comprising very soft organic peat, intermediate permeability silty soils, tailing deposits, some highly weathered residual soils among others.

The standard penetration test (SPT) is the dominant in-situ test for soil investigation, but very often the site characterization is complemented by other in situ and laboratory tests. The use of the CPT has gradually increased in Brazil being now recognized as a standard technique in soft soils construction. In fact there is a long history of CPT in Brazil. Two important Technical Report describing the CPT Brazilian experiences are Rocha-Filho & Schnaid (1995) at CPT`95 and Danziger & Schnaid (2000) at the Brazilian Symposium on In-situ Site Investigation (BIC, 2000). History, equipment, engineering practice and research, design methods and recommendations are presented. Research at Brazilian universities set the ground for the important contributions required for Brazilian practice (e.g. Schnaid et al. 2004, Coutinho et al. 2004, Schnaid, 2005, Vianna da Fonseca & Coutinho, 2008, Coutinho, 2008 and others). The impact of economy growth on infrastructure requires new and important projects to be developed in areas such as rail, roads, building, defense, energy, among others. These construction activities are demanding for more extensive and consistent geotechnical investigations in which the CPT is being adopted. Figure 1 shows an example of CPT investigation performed for the BR-101 motorway duplication in Florianópolis, southern Brazil.

Figure 1. CPT rig on BR-101 Florianópolis, SC, Brazil (www.geoforma.com.br)

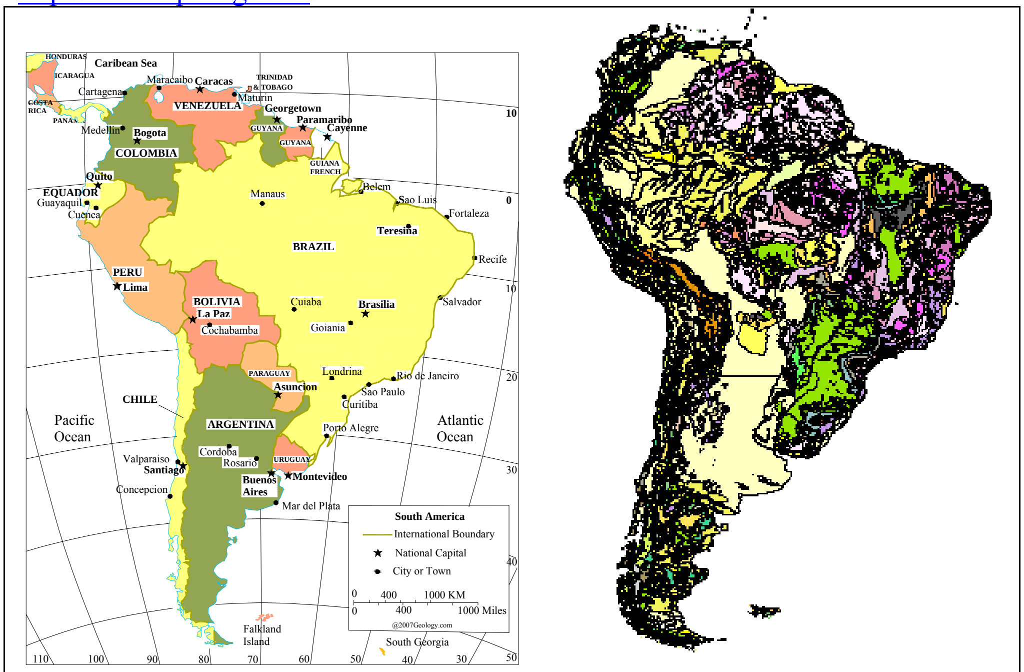
2 OVERVIEW OF THE REGION AND GEOLOGICAL SETTING

Figure 2a shows a map of South America countries, an area distributed along 11.3 million square kilometers. Figure 2b and 3 show the Geological Map in scale

1:5.000.000, describing the main soil formations. Detailed Information can be obtained in http://www.cprm.gov.br/publique/media/americasul.pdf.

Brazil is the biggest country of the South America and one of the biggest in the world. It has a land surface of about 8.5 million square kilometers and a population in the order of 190 million. The country is divided into five regions: North, Northeast, Midwest, Southeast and South (Figure 4) and presents a wide variation of climate: equatorial, tropical, semi-arid, atlantic tropical, tropical of altitude and subtropical (Figure 5). The equatorial climate is localized in the Amazonian region, where the rainfall is above 2.500mm/year and temperatures are high during the whole year. The tropical climate is characterized for high temperature (in general above 20ºC), with well defined humid summer and dry winter, presenting rainfall around 1500 mm/year. The semi-arid climate is characterized for high temperature (average of 27ºC), limited, irregular and not well distributed rainfall (around to 200mm / year). The Atlantic climate or humid tropical is characterized for temperatures around 30^0 C, and rainfall around 2000 mm/year. The tropical of altitude climate, presents average temperatures varying between 15ºC to 21ºC, and intense rainfall in summer. Frosts occur in winter. The subtropical climate is characterized for hot summer and cold winter, presenting rainfall around 1000 to 2000 mm/year, and average temperature around 20ºC (www.suapesquisa.com/clima/).

The vast area of Brazil encompasses a great variety of geological environments. The Brazilian Federal Agency CPRM developed in 2006 a Geological Survey expressed in the form of a Geodiversity Map (1:2.5000.000), illustrated in Figure 6 - http://www.cprm.gov.br.



(a) (b)

Figure 2. Maps of South America (a) distribution of the countries (b) basic geology.

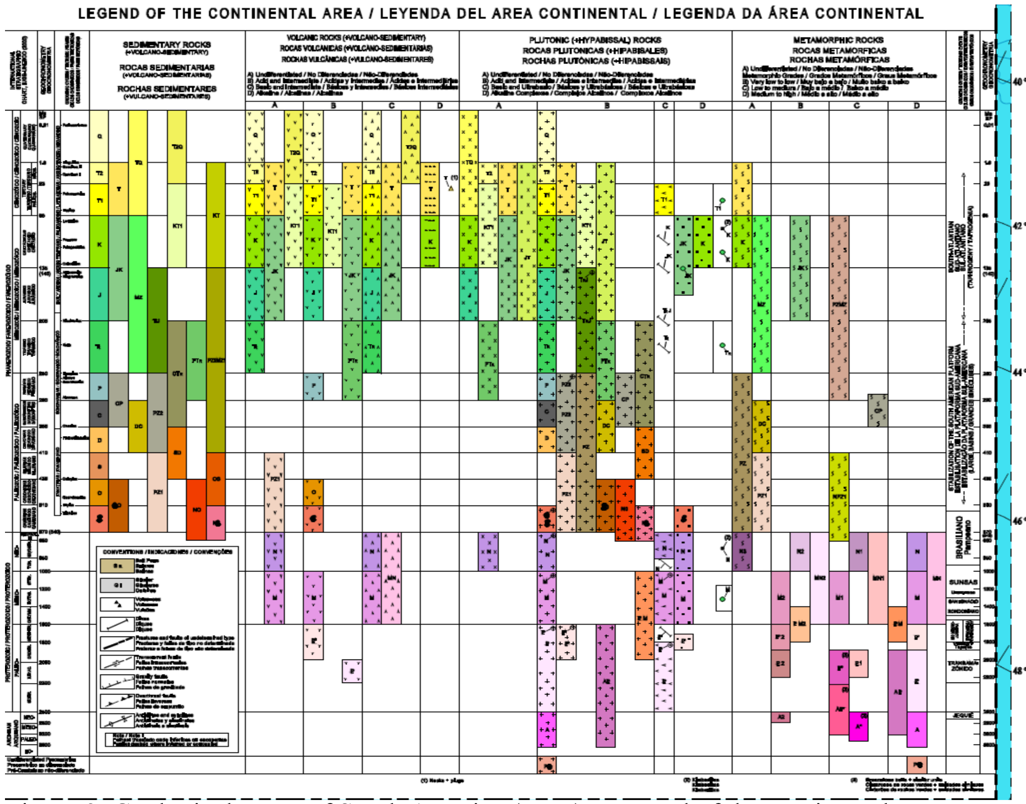


Figure 3. Geological Maps of South America (cont.) - Legend of the continental area.

The geosystem of Brazil was classified in 23 geological-environmental domains, subdivided in 108 geological-environmental units. The product represents the influence of geology on the suitability, limitations and potentialities in view of use and occupation to: the execution of civil works, agriculture, pollutant sources, groundwater resources, mineral potential, environmental aspects and touristic potential. Four examples of geological-environmental domains with their geological-environmental units and their distribution in the national map are presented in Figure 7. The correspondent influence of the geology in view of use and occupation to civil works is also presented. As referred to fundamental geological concepts, Brazil has one of the most significant contributions produced worldwide, with the conclusion in 2005 of the Geological Map of Brazil to Millionth scale 1:1.000.000 – http://www.cprm.gov.br.

There is great variety of natural soil deposits encountered in Brazil. In the context of this report, three important groups are the sedimentary sands, clays, silts and tills, sometimes in very soft or loose condition, the extensive in situ weathered soil profile (the so-called residual, tropical, lateritic and saprolite soils) and the colluviums deposit. There are many populated cities in Brazil along the coastline where the occurrence of these types of soil deposits is frequent and is the reason for important geotechnical challenges.

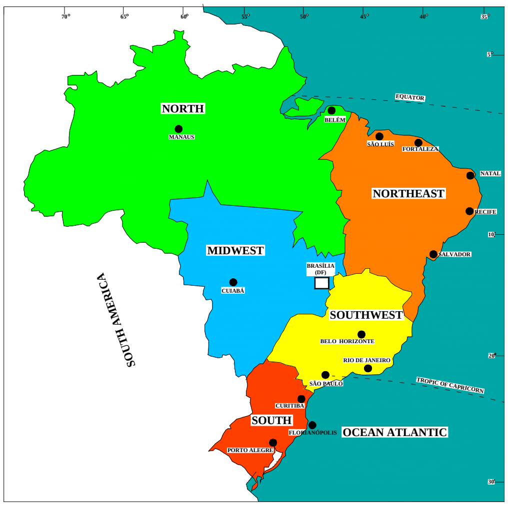


Figure 4. Map of Brazil showing the enlarge Regions

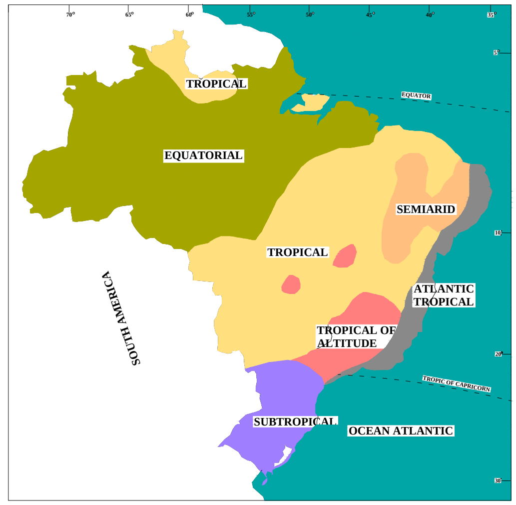


Figure 5. Map of Brazil showing a summary climate distribution

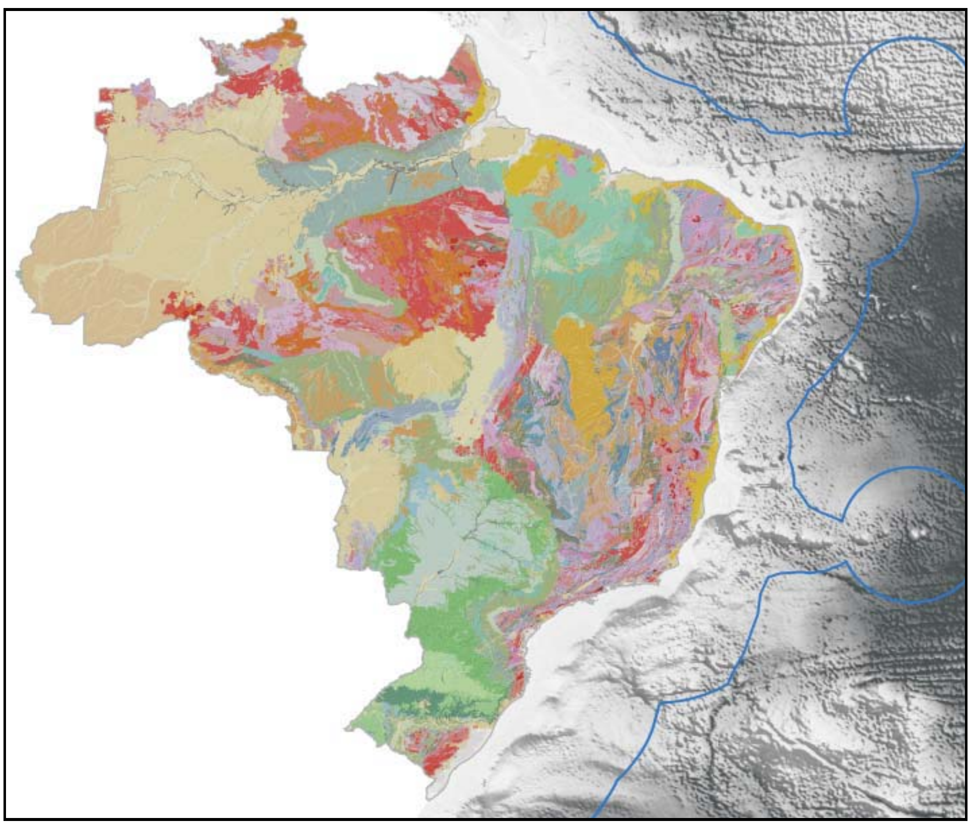
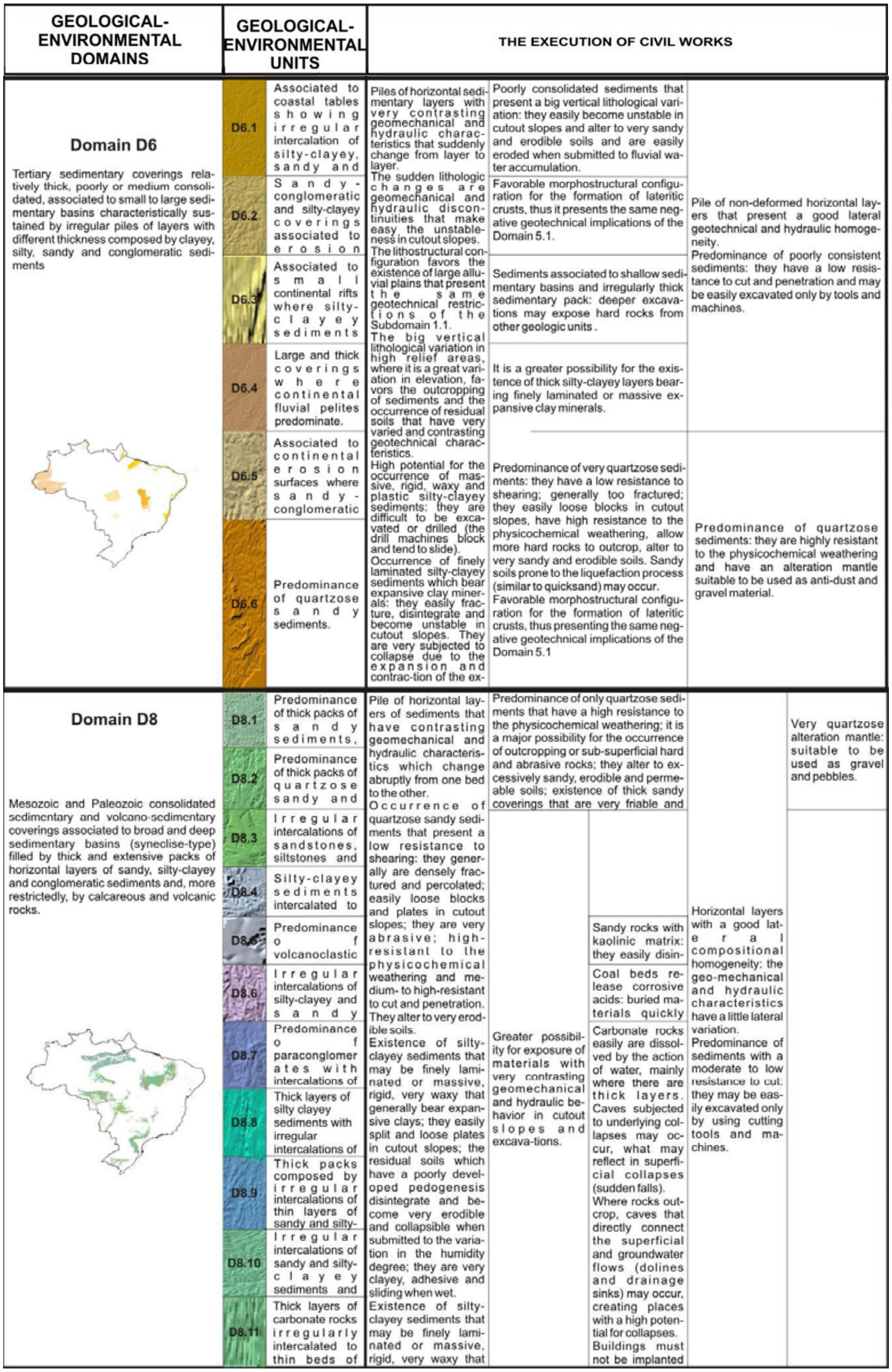


Figure 6. Geodiversity Map of Brazil, Scale 1:2.500.000, 2006, including the Continental Platform - Federal Government, Ministry of Mines and Energy, CPRM – Geological Survey of Brazil (http://www.cprm.gov.br)



GEOLOGICAL-ENVIRONMENTAL DOMAINS	GEOLOGICAL-ENVIRONMENTAL UNITS		THE EXECUTION OF CIVIL WORKS				
Domain D6 Tertiary sedimentary coverings relatively thick, poorly or medium consolidated, associated to small to large sedimentary basins characteristically sustained by irregular piles of layers with different thickness composed by clayey, silty, sandy and conglomeratic sediments	D6.1	Associated to coastal tables showing irregular intercalation of silty-clayey, sandy and	Piles of horizontal sedimentary layers with very contrasting geomechanical and hydraulic characteristics that suddenly change from layer to layer. The sudden lithologic changes are geomechanical and hydraulic discontinuities that make easy the unstableness in cutout slopes. The lithostructural configuration favors the existence of large alluvial plains that present the same geotechnical restrictions of the Subdomain 1.1. The big vertical lithological variation in high relief areas, where it is a great variation in elevation, favors the outcropping of sediments and the occurrence of residual soils that have very varied and contrasting geotechnical characteristics. High potential for the occurrence of massive, rigid, waxy and plastic silty-clayey sediments: they are difficult to be excavated or drilled (the drill machines block and tend to slide). Occurrence of finely laminated silty-clayey sediments which bear expansive clay minerals: they easily fracture, disintegrate and become unstable in cutout slopes. They are very subjected to collapse due to the expansion and contrac-tion of the ex-	Poorly consolidated sediments that present a big vertical lithological variation: they easily become unstable in cutout slopes and alter to very sandy and erodible soils and are easily eroded when submitted to fluvial water accumulation.		Pile of non-deformed horizontal layers that present a good lateral geotechnical and hydraulic homogeneity. Predominance of poorly consistent sediments: they have a low resistance to cut and penetration and may be easily excavated only by tools and machines.	
	D6.2	Sandy-conglomeratic and silty-clayey coverings associated to erosion		Favorable morphostructural configuration for the formation of lateritic crusts, thus it presents the same negative geotechnical implications of the Domain 5.1.			
	D6.3	Associated to small continental rifts where silty-clayey sediments		Sediments associated to shallow sedimentary basins and irregularly thick sedimentary pack: deeper excavations may expose hard rocks from other geologic units .			
	D6.4	Large and thick coverings where continental fluvial pelites predominate.		It is a greater possibility for the existence of thick silty-clayey layers bearing finely laminated or massive expansive clay minerals.			
	D6.5	Associated to continental erosion surfaces where sandy-conglomeratic		Predominance of very quartzose sediments: they have a low resistance to shearing; generally too fractured; they easily loose blocks in cutout slopes, have high resistance to the physicochemical weathering, allow more hard rocks to outcrop, alter to very sandy and erodible soils. Sandy soils prone to the liquefaction process (similar to quicksand) may occur. Favorable morphostructural configuration for the formation of lateritic crusts, thus presenting the same negative geotechnical implications of the Domain 5.1		Predominance of quartzose sediments: they are highly resistant to the physicochemical weathering and have an alteration mantle suitable to be used as anti-dust and gravel material.	
	D6.6	Predominance of quartzose sandy sediments.					
Domain D8 Mesozoic and Paleozoic consolidated sedimentary and volcano-sedimentary coverings associated to broad and deep sedimentary basins (syneclise-type) filled by thick and extensive packs of horizontal layers of sandy, silty-clayey and conglomeratic sediments and, more restrictedly, by calcareous and volcanic rocks.	D8.1	Predominance of thick packs of sandy sediments,	Pile of horizontal layers of sediments that have contrasting geomechanical and hydraulic characteristics which change abruptly from one bed to the other. Occurrence of quartzose sandy sediments that present a low resistance to shearing: they generally are densely fractured and percolated; easily loose blocks and plates in cutout slopes; they are very abrasive; high-resistant to the physicochemical weathering and medium- to high-resistant to cut and penetration. They alter to very erodible soils. Existence of silty-clayey sediments that may be finely laminated or massive, rigid, very waxy that generally bear expansive clays; they easily split and loose plates in cutout slopes; the residual soils which have a poorly developed pedogenesis disintegrate and become very erodible and collapsible when submitted to the variation in the humidity degree; they are very clayey, adhesive and sliding when wet. Existence of silty-clayey sediments that may be finely laminated or massive, rigid, very waxy that	Predominance of only quartzose sediments that have a high resistance to the physicochemical weathering; it is a major possibility for the occurrence of outcropping or sub-superficial hard and abrasive rocks; they alter to excessively sandy, erodible and permeable soils; existence of thick sandy coverings that are very friable and		Horizontal layers with a good lateral compositional homogeneity: the geo-mechanical and hydraulic characteristics have a little lateral variation. Predominance of sediments with a moderate to low resistance to cut: they may be easily excavated only by using cutting tools and machines.	Very quartzose alteration mantle: suitable to be used as gravel and pebbles.
	D8.2	Predominance of thick packs of quartzose sandy and					
	D8.3	Irregular intercalations of sandstones, siltstones and		Greater possibility for exposure of materials with very contrasting geomechanical and hydraulic behavior in cutout slopes and excava-tions.			
	D8.4	Silty-clayey sediments intercalated to					
	D8.5	Predominance of volcanoclastic			Sandy rocks with kaolinic matrix: they easily disin-		
	D8.6	Irregular intercalations of silty-clayey and sandy			Coal beds release corrosive acids: buried materials quickly		
	D8.7	Predominance of paraconglomerates with intercalations of			Carbonate rocks easily are dissolved by the action of water, mainly where there are thick layers. Caves subjected to underlying collapses may occur, what may reflect in superficial collapses (sudden falls). Where rocks outcrop, caves that directly connect the superficial and groundwater flows (dolines and drainage sinks) may occur, creating places with a high potential for collapses. Buildings must not be implanted		
	D8.8	Thick layers of silty clayey sediments with irregular intercalations of					
	D8.9	Thick packs composed by irregular intercalations of thin layers of sandy and silty-					
	D8.10	Irregular intercalations of sandy and silty-clayey sediments and					
	D8.11	Thick layers of carbonate rocks irregularly intercalated to thin beds of					

Figure 7. Geodiversity Map of Brazil – Geological environmental domains - http://www.cprm.gov.br

GEOLOGICAL-ENVIRONMENTAL DOMAINS	GEOLOGICAL-ENVIRONMENTAL UNITS		THE EXECUTION OF CIVIL WORKS			
Domain D19 Non- or little deformed, late- to post-tectonic granitoid complexes that are composed by granites which have 	D19.1	Predominance of alkalic-monzo-syenites.	Predominance of highly crystalline rocks whose mineralogy is mostly constituted by feldspars and, more restrictedly, quartz: fresh rocks highly resistant to cut and penetration; the use of explosives is needed to disintegrate them; they alter to clayey-silty-sandy soils; the little evolved soils are very erodible and easily become unstable in cutout slopes; they favor natural mass movements; not suitable for building material specially in installations exposed to the accumulation of rainwater. Granitic rocks alter very differently and almost always leave blocks and boulders merged into the soils: the depth of the rocky substratum is very irregular; even when soils are deep and well evolved there is a great possibility for the existence of fresh rock blocks and boulders that may make difficult any excavation or drilling work. These are terrains that require detailed geotechnical studies supported by a close drilling grid, what makes very expensive the planning and the execution of works. Granites use to be densely fractured in many directions in the border zones of the late- and post-tectonic massifs: the easily loose blocks in cutout slopes.		Highly coherent rocks that have a good textural and mineralogic homogeneity with predominance of feldspars and quartz: high resistance to compression; poor primary porosity. Moderate to high resistance to the physicochemical weathering; they are suitable to be used as concrete aggregates in building foundations and other uses. They alter to clayey-silty-sandy soils: the partial alteration mantle is good to be used as gravel. The residual soils with an advanced pedogenesis have a good compaction capacity; they are moderately plastic, little permeable and little erodible, so they	Predominance of granites that have a good textural and compositional homogeneity: good lateral and vertical geomechanical homogeneity.
	D19.2	Predominance of monzo-granodio-rites.				
	D19.3	Aluminous granites.				
	D19.4	Staniferous granites.				
	D20.1	Predominance of alkalic-monzo-syenites.		Greater possibility for the existence of granites with isotropic to anisotropic texture: they are rocks whose geomechanical characteristics are more heterogeneous and with a greater possibilitiy to bear weak structural planes.		
Domain D20 Non- or little deformed, syn- to late-tectonic granitoid complexes derived from several magmatic pulses that have a big variation in the chemico-mineral composition, granulation and color.	D20.2	Predominance of monzo-granodiorites.				
	D20.3	Aluminous granites.				
Domain D23 Granitic-gneissic-migmatitic and granulitic complexes composed by an intricate association of rocks that resulted from the partial or total melting of very old rocks that were submitted to the superposition of several compressive tectono-metamorphic events along the geologic history of the Earth, under high temperature and pressure conditions. So, they were melted, re-melted, 	D23.1	Predominance of orthoderived granitic-gneissic-	Complex association of small or large bodies of rocks with very diverse and contrasting geomechanical and hydraulic characteristics. Very ductile- and brittle-tectonized rocks containing many planar surfaces disposed in several directions and several dip angles: they easily loose blocks and become unstable in cutout slopes, mainly when partially altered. They alter very heterogeneously to clayey-silty-sandy soils: the depth of the rocky substratum is usually very irregular, it may vary from shallow to deep in short distances; the little-evolved residual soils generally bear expansive clay minerals and have very different alteration degree and physicochemical characteristics; they are very erodible if submitted to the accumulation of rainwater and easily become unstable in cutout slopes; they enlarge much the natural mass movements, even where the declivity is not pronounced; in this case they are not suitable to be used as building material in works that are subjected to the accumulation of rainwater; they may randomly contain blocks and boulders that may be moved in cutout slopes and turn unstable the buildings whose foundations are partially supported by them. Linear works require geotechnical studies supported by a close-spaced drilling grid and by a large number of technologic analyses on material collected in different	Predominance of lithologies composed by an alternation of isoriented micaceous mineral (biotite)-rich bands and non- or little-oriented prismatic mineral (quartz and feldspars)-rich bands: they constitute geomechanical and hydraulic discontinuities that make easy the fluid percolation, the weathering processes and the	Predominance of rocks that alter to clayey-silty-sandy soils: the partial alteration mantle is suitable to be used as gravel; the residual soils with an advanced pedogenesis have a good compaction capacity, low to moderate permeability, are moderately plastic and naturally little erodible. In this case, in opposition to little-evolved soils, they are suitable to be used as building material.	
	D23.2	Predominance of paraderived				
	D23.3	Predominance of paraderived gneisses.				
	D23.4	Ortho- and paraderived undifferentiated migmatites.				
	D23.5	Gneissic-migmatitic rocks that contain small and large bodies of				
	D23.6	Gneissic-migmatitic rocks that contain small and large		Orthoderived granulitic rocks and gneisses are very resistant to cut and penetration and moderate to very resistant to the physicochemical weathering; greater potential for the existence of many blocks and		Predominance of crystalline rocks that are very coherent and are mainly composed by feldspars: high resistance to compression; poor primary porosity; moderate to high resistance to the physicochemical weathering.
	D23.7	Gneissic-migmatitic rocks that contain small and large				
	D23.8	Predominance of orthoderived gneisses.				

Figure 7 (cont). Geodiversity Map of Brazil – Geological environmental domains - http://www.cprm.gov.br

3. GEOTECHNICAL CHALLENGES

3.1 Site Investigation Practices

South America has one of the most unbalanced distributions of resources of all regions in the world and in this context it is difficult to produce an overview of the situation on the continent as a whole. As previously stated, very often there are reports of small contractors operating regionally which we were unable to identify, so a precise acquisition of the continent experience was not possible and substantial uncertainty inevitably exists. Despite these uncertainties an attempt is made to identify local site investigation practices.

Existing experience in the continent is mainly related to the electrical cone and piezocone. Combination of different techniques by coupling the robustness of the cone with additional information derived from other sensors (seismic cone, cone-pressuremeter, resistivity cone) is restricted to research environment. Whereas the SPT is the most dominant in situ testing technique in Brazil, there has been a steady increase in the use of the CPT in the past 15 years. The piezocone represents a fundamental part in almost every major infra-structure site investigation program located in regions where low bearing capacity soil formations prevail. Cone penetration tests are carried out by specialist site investigation contractors located around the main cities. Although international companies are operating in Brazil, their market is mainly focused on offshore testing since there are no dedicated ships or computerized underwater rigs in the country.

On searching for economic deposits of minerals and oil and gas exploration, many international companies are now established in Chile, Ecuador, Peru, Colombia and Venezuela.

To our knowledge there is no systematic experience on the CPT in Bolivia, Paraguay, Uruguay, Guyana, French Guiana and Suriname.

Experience with the CPT in South America is generally associated with the prediction of soil properties in soft, compressible and saturated deposits. In some regions the CPT is becoming routine for the design of tailing dams and other environmental applications. CPT data is not frequently used for pile design because SPT is dominant.

Assessment of the potential for soil liquefaction is an issue of concern in South America, especially for dynamic liquefaction along the Andes (Figure 8). Approaches published by Wang (1979), Robertson and Wride (1998), Juang et al (2003), Moss et al (2006), Robertson (2009), among others, are currently used in the region.

3.2 Major geotechnical issues

Brazil is a country with a diversity of geology and climate that has many necessities to become a developed nation. In this way, in the past years there have been several important engineering technical activities for construction of buildings and infrastructure (Figure 9). Important developments comprise highway project and construction, airport, industrial ports, mining activity particularly related to tailing dam projects, impacts of increasing population density in urban areas with natural hazards relative to slope stability and flooding. Examples of the main geotechnical challenges comprise work on soft ground, shallow and deep foundation, deep excavations, slope stability and geotechnical condition of tailing deposits.

A relatively new and significant geotechnical challenge arises from the effects of climate change on infrastructure, environment and national heritage, e.g. higher intensity rainfall (landslides), flooding and drying. In this context, in the last recent years some important events were held in the South and Southeast regions of Brazil in past years.

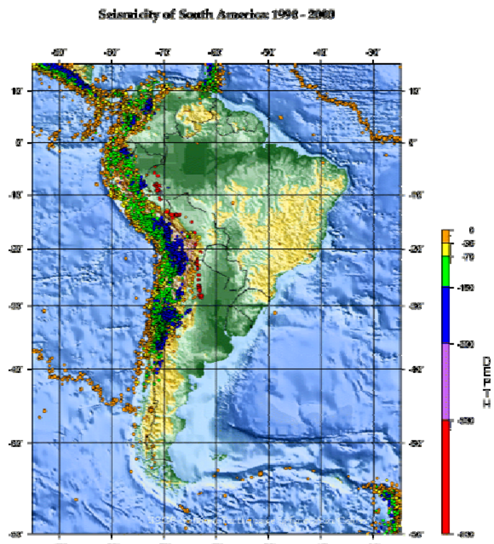


Figure 8. Seismicity chart for South America (http://earthquake.usgs.gov/earthquakes)

Figure 9. CPT rig with 200 kN capacity, Investigation for building construction in Curitiba–PR, Holocene deposit – www.fugroinsitu.com.br

4 CPT EQUIPMENT AND PROCEDURES

4.1 Standards & Procedures

In Brazil there is a national standard for CPT testing - ABNT (1991), NBR 12069. In addition, contractors, and those who specify the testing also take direct account for the IRTP – International Reference Test Procedure published by the International Society for Soil Mechanics and Geotechnical Engineering in 1999 (ISSMGE, 1999). Some other countries tend to relay on the ASTM Standard. The book of Lunne *et al* (1997) is also used as a reference, both for conducting the tests and for test interpretation. Danziger & Schnaid (2000) presents a report (TC-In Situ Investigation from the ABMS – Brazilian Society of Soil Mechanics and Geotechnical Engineering) with recommendation for performance and interpretation of piezocone tests covering both Brazilian and international experiences.

4.2 CPT Equipment (Types of Cone Penetration Test Equipment)

Most onshore and near shore operations are conducted by local contractors that either import their equipment from Europe and the USA or alternatively build their own CPT probes and pushing devices. Local equipments generally follow international referenced test procedures. Currently there are some 15 CPT units operating in Brazil, the majority built on light hydraulic rigs anchored by propeller (auger) blades with capacity between 100 and 200kN. Some pushing equipment is multi functional and can be used for many field activities (Figure 10). Argentina has few companies operating locally: one in the capital Buenos Aires and small contractors using their own CPT probes (no pore pressure measurements). A local contractor in the northern region focuses their operation on pile design.

Most cones are 10 cm^2 cones capable of measuring q_c, f_s and u. Most cones are imported but there are some produced in Brazil (Figure 11). For the piezocone, the pore pressure transducer filter is almost always located just behind the shoulder (giving the so-called "u_2"measurement). COPPE/UFRJ has routinely used a dual piezocone (u_1 and u_2) since 1996. The saturation fluid can be de-aired water, silicon oil, glycerine, mineral oil or grease. A study in tropical unsaturated soil using the slot filter with automotive grease is presented by Mondelli et al. (2009).

In cases where cone tests are part of the soil investigation programmers, CPTU is the most frequently adopted technique (around 70 %), followed by CPT (20%) and SCPTU (around 10%). In countries where seismicity is important the use of SCPTU is in higher percentage.

In general, data acquisition systems are imported from Europe and the USA or alternatively the local companies build their own systems. Most consultant and contractors use self-made spreadsheet software for data processing.

(a) Cone equipment for 200 kN

(b) Cone equipment for 200 kN, test in platform

(c) Cone equipment for 200 kN, in soft soil

(d) Cone equipment for 200 kN, in soft soil

Figure 10. Examples of CPT units operating in Brazil – Cone equipment for 100 - 200 kN www.geoforma.com.br

Figure 11. Details of Cone produzed in Brazil – www.geoforma.com.br

4.2.1 Challenges with equipment and procedures

Challenges are different across the continent. Whereas in many countries there are no systematic experiences in running the test, there are regions were the test is carried out on a routine basis. This last case includes Brazil, where challenges in equipment and procedures fall in five categories:

- Reduce import dependence, since there are no companies manufacturing CPT equipments commercially in the region. This problem also impacts equipment maintenance.
- Improve personnel qualification and training for site investigation work with CPT systems.
- Develop equipment, procedures and interpretation methods applied to non-textbook materials, particularly in residual (mature and young) soils, colluviums and tailing deposits, in saturated and unsaturated conditions.
- Develop interpretation methods for assessing soil parameters in very soft ground exhibiting very high water content and organic matter.
- Improve penetration capability to deal with very hard layers.

4.2.2 Contractors

Cone penetration tests are carried out by specialist site investigation contractors. Most contractors are based in the South or Southeast regions located at the main towns. The equipment has to be transported long distances across the country. Some good examples of the most prominent CPT contractors are (in alphabetic order):

- Damasco Penna (www.damascopenna.com.br), based in São Paulo, SP, Southeast region
- Fugro - In Situ (www.fugroinsitu.com.br), based in Curitiba, PR – South region
- Geoforma (www.geoforma.com.br) based in Joinville, SC – South region

In general, contractors struggle to keep updated to the latest developments in international practice in all aspects of equipment and procedures. In addition, some Brazilian universities have CPT equipment and operate on a commercial basis, but this is no longer routine in Brazil.

5 CPT INTERPRETATION

The textbook published by Lunne et al. (1997) is the major reference for CPT interpretation, for both identification of soil types and stratigraphy and assessment of soil parameters for engineering design or for design based directly on the measured CPT/CPTU parameters. More recently, Brazilian consultants are beginning to use the textbook published by Schnaid (2009). As previously mentioned, South American contractors and consultants tend to develop their own spreadsheet for interpretation of test data. Commercial softwares are also available and are used occasionally.

5.1 Soil Stratigraphy Interpretation (Soil Classification and Stratigraphy)

Soil type is often interpreted by CPT contractors using classification charts such as those proposed by Douglas & Olsen, 1981; Senneset & Janbu, 1985; Robertson et al, 1986, as well as others (Robertson, 1990; Jefferies & Davies, 1991).

It is generally understood that the CPT classification charts do not provide accurate predictions of soil type based on grain size distribution, but they have been set to provide a guide for soil type. Experience shows that there are deficiencies and limitations in this approach, particularly in geological deposits where pore pressure measurements are not reliable or cannot be obtained. It is common practice in Brazil to have minimum site-specific "calibration" from SPT boreholes.

There are recent efforts from the geotechnical community (including Brazil) to characterize aging and cementation effects in granular material. q_c and G_0 profiles can be directly used to evaluate the possible effects of stress history, degree of cementation and ageing, as already recognised by Eslaamizaad & Robertson (1997). Figure 12 illustrates one of these approaches from results presented by Schnaid et al. (2004) including Portuguese data from FEUP experimental site. The variation of G_0 / q_c ratio was expressed by upper and lower bounds. The upper bound for uncemented material can be assumed as a lower bound for cemented soils and a tentative new upper bound for cemented materials can be expressed as (Schnaid et al. 2004):

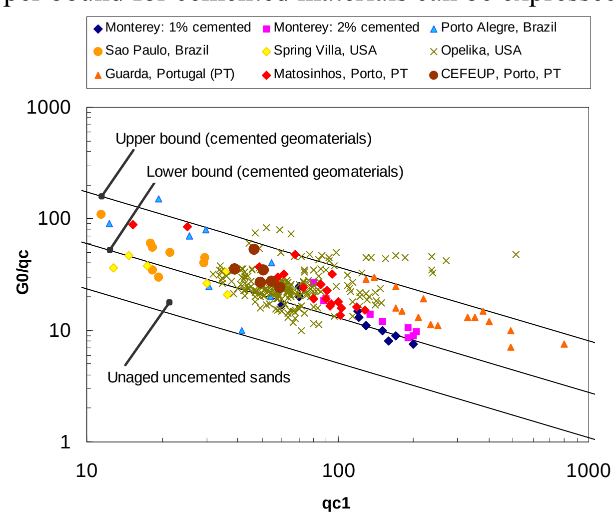


Figure 12. Relationship between G_o and q_c for residual soils (Viana da Fonseca & Coutinho, 2008, completed from Schnaid et al. 2004).

$$\left.\begin{array}{ll} G_0 = 800\sqrt[3]{q_c \sigma'_v p_a} & \text{upper bound : cemented} \\ G_0 = 280\sqrt[3]{q_c \sigma'_v p_a} & \text{lower bound : cemented} \\ & \text{upper bound : uncemented} \\ G_0 = 110\sqrt[3]{q_c \sigma'_v p_a} & \text{lower bound uncemented} \end{array}\right\} \quad (1)$$

5.2 Derivation of Soil Parameters

Many empirical correlations are used in practice to interpret CPT results. It is rather difficult to establish what the current practice in South America is and our Report may be somewhat biased by the Brazilian experience. Prediction of soil parameters in both clay and sand from piezocone test results are generally made on the bases of standardized methods and procedures. Undrained shear strength, stress history, stress state, stiffness and coefficient of consolidation are estimated from cone penetration tests in clay, whereas relative density, internal friction angle, state parameter and soil stiffness are estimated in granular materials. Table 1 indicates the methods that are most commonly adopted in the region.

In Brazilian geotechnical practice, piezocone data are often used in combination with vane data to obtain undrained strength S_u profiles. The undrained shear strength usually is estimated from CPTU using the correlation $q_t = N_{kt} S_u + \sigma_{v0}$, where N_{kt} is an empirical cone factor and σ_{v0} is the total in situ vertical stress. Average values of N_{kt} for Brazilian soft clays deposits have been found to be in the range of 9 to 18, with an average result of 13. This mean value is calibrated from both field vane test (more common) and triaxial UU and CIU tests (see Danziger & Schnaid, 2000; Danziger, 2007 and Coutinho, 2008). Recently results reported for soft clay deposits in Rio de Janeiro (Almeida et al. 2010) show a large range of N_{kt} values that are generally smaller than values reported in other sites. These results suggest that for large and important projects, site-specific correlations are required. In addition, research is indicating that S_u values can be estimated directly as a function of excess porewater pressure as $S_u = (u_2 - u_0) / N_{\Delta u}$ (Coutinho, 2008).

The stress history of Brazilian soft clays deposits are usually obtained from oedometer tests. In addition, empirical estimates of preconsolidation pressure can be obtained from field CPTU testing data using the method proposed by Chen & Mayne (1996): $\sigma'_P = 0.305\ (q_t - \sigma_{v0})$. Brazilian experience indicates that empirical values yielded from this correlation are somewhat higher than the best estimation of in situ values.

Coefficients of consolidation are calculated from piezocone dissipation tests using Houlsby and Teh's method (1988) adopting standard procedures proposed in the literature (Lunne et al. 1997; Schnaid, 2009). Values of C_h are representative of the overconsolidated range and are calculated for 50% pore-pressure dissipation at the cone shoulder (u_2). The clay stiffness index $I_r = G/S_u$ for Brazilian clays are observed to be in the range of 50 to 150. Assessment of the coefficient of consolidation C_h in the NC range is attained from the empirical rule C_h (NC) = (RR / CR) x C_h (piezocone). The coefficient of consolidation for vertical flow C_v requires the horizontal to vertical permeability ratio to be estimated independently: $C_v = (k_v/k_h) \times C_h$.

In relation to soil stiffness, estimation of the small strain stiffness (G_0) for granular materials can be made for preliminary design considering the proposed lower bound equations described in 5.1 (Schnaid, 2004). The direct use of the seismic cone (SCPTU) to measure G_0 is incipient in the region but appears to be growing.

First estimation of an operational modulus, as the secant Young`s modulus, E_s, is generally obtained from equation E_s = n qc, knowing that *n* depends on the type of material, sand relative density, among other factors. For sand, the minimum accepted *n* value usually is usually 2.5. Bellotti et al. 1989 proposal is a reference method for assessing OCR and aging effects. In Brazil there is a local database to estimate E_s in residual soils both in natural and compacted condition (e. g. Barata, 1983 and Barata & Danziger, 1995).

Recent studies have been developed to assess geotechnical properties in silty soils, and other intermediate permeability geomaterials (K in the range of 10^{-5} to 10^{-8} m/s), an issue that is far from being satisfactory resolved (Schnaid et al. 2004, Schnaid, 2005 and others). A non-dimensional parameter V = vd/Cv has been proposed (Randolph and Hope, 2004), where v = penetration rate, d = probe diameter and C_v = coefficient of consolidation. The drainage characterization curve (V versus degree of drainage U) can be adopted to identify the transition from drained to partially drained to undrained penetration. A general recommendation is to avoid penetration ratios that yield dimensionless velocities within the range of 10^{-1} to 10^{+2}. In this range, partial drainage is expected to occur and properties assessed from field test interpretation can be ovestimated, in particular the undrained shear strength (Schnaid et al. 2004, Schnaid, 2005, Schneider et al. 2007, and Schnaid, 2009).

Table 1. CPT Interpretation - methods most commonly adopted in the region

Soil Parameters	Key References
Soil classification	Douglas & Olsen (1981); Senneset & Janbu (1985); Robertson et al (1986), Robertson (1990)
In situ stress state (K_o)	Mayne & Kulhawy (1990)
Constrained modulus (M)	Kulhawy & Mayne (1990); Duncan & Buchignani (1976)
Shear modulus (G_{max})	Tanaka et al (1994); Powell & Butcher (2004); Schnaid (2005)
Stress history (σ'_p , OCR)	Schmertmann (1978) ; Jamiolkowski et al (1985) ; Mesri, (1975; Mayne (1991)
Undrained strength (S_u)	Bearing capacity formulation with N_{kt} derived from calibration
Coefficient of consolidation (C_h)	Teh & Houlsby (1991);
Relative density (RD)	Jamiolkowski et al (1985)
Angle of internal friction (ϕ')	Robertson & Campanella (1983).

6 CPT APPLICATIONS

6.1 General

Identification of ground profile and assessment to design parameters, as described in Section 5, are the most common applications of CPT in Brazil. Marine and alluvial costal deposits spread along dense populated areas are suitable for CPT based site investigation, in particular the soft clay deposits where the piezocone is now established as a routine site investigation tool in major infra-structure design projects. Experience gained in clay deposits encouraged the use of the CPT in other applications comprising very soft organic peat, intermediate permeability silty soils, tailing deposits, some highly weathered residual soils among others.

In pile design, the LCPC method and recommendations from Eurocode 7-3 are adopted, although current practice is essentially supported by SPT correlations. In the case of saturated clays a method based on piezocone data proposed by Almeida et al. (1996) is often adopted. In Brazil, a contribution from Barata is often adopted to estimate settlements in shallow foundation resting in natural deposits and compacted soils (e.g. Barata, 1983 and Barata & Danziger, 1995).

For liquefaction, CPT-based approach is established by relating the measured cone resistance to the cyclic resistance ratio (CRR) introduced by Seed & Idriss (1971). The most common methods for assessing liquefaction potential are: Wang (1979), Robertson and Wride (1998), Juang et al (2003), Moss et al (2006) and Robertson (2009). There seems to be no consensus in the area.

To the authors' knowledge, there is no standardized practice for evaluation of ground improvement. However, this is clearly a growing field.

6.2 Geo-environmental applications

There appears to be no systematic experience in South America with environmental cones. Measurements of pH, resistivity, redox potential, laser induced fluorescence and temperature are restricted to research activities. The use is yet incipient in practice.

In Brazil main applications are the evaluation of contaminated sites by hydrocarbons, municipal solid waste and the contamination of aquifers with salt water. The resistivity cone the most common test in the region. Recently, some companies have acquired MIP (Menbrane Interface Probe) integrated with CPT systems for recording the amount of organic volatiles.

7 RESEARCH AND FUTURE TRENDS

A recent publication reports the research experience on eleven Brazilian Test Sites (Cavalcante et al., 2007).The requirements for a test site to be included in the Report were: (i) it should be actively involved in research and (ii) plate or pile load test should be provided. The report provides, information on the origin of the soils, the investigation program carried out (comprising laboratory and in situ tests, including CPTs), as well as the database on pile load tests and plate tests (foundations study).

The main goals for the report were twofold: (i) develop methods envisaged to support special geotechnical engineering projects; (ii) carry out university research, not necessarily connected with applied engineering. The eleven sites are COPPE/UFRJ - PUC-RJ, POLI/USP, EESC/USP, UNICAMP, UNESP/FEB, UNESP/FEIS, UNB, UFPR, UEL/PR, UEM/PR and UFPE, most of which were established in 1988, except the Sarapuí established in 1974. Only two of these sites are on soft clay; the others are in tropical deposits soils, including the study on unsaturated soils.

Comprehensive site investigation has been carried out in a number of other soft clay sites, as reported by Danziger (2007). These experiences are related to major engineering projects like Sesc-Senac in Rio de Janeiro (Almeida, 1998) and Ceasa in

Porto Alegre (Soares, 1996, Schnaid et al. 1997) or describe research activities that are not aimed at investigating foundation performance, e. g. Clube Internacional at Recife, PE, launched in 1978 (Coutinho et al. 1993, Coutinho, 2007). Recent papers summarizing the main information regarding Sarapuí and the two sites SESI and Clube Internacional have been published by Almeida & Marques (2003) and Coutinho (2007).

Table 2 shows a summary of the in situ test correlations developed for the Recife soft clay sites to obtain OCR, K_0, S_u and M. Geotechnical parameters obtained from local correlations were compared to the correspondent reference values: OCR and M from oedometer test, $K_0 = (1 - \sin \phi') \, OCR^{\sin \phi'}$ **,** S_u – triaxial and vane tests. Comparisons to in situ test based correlations are summarized in Columns 5 and 6 and are shown to be in the range of measured values.

Another important topic is the study of bonded granular material (see Schnaid et al. 2004; Coutinho et al. 2004 and Vianna da Fonseca & Coutinho, 2008). To illustrate this topic, it is worth mentioning a paper submitted to this conference, presenting a discussion on the interpretation of CPTU data for stratigraphic logging of a sedimentary deposit and two residual soil deposits from Brazil and Portugal (De Mio et al., 2010). Recently, Giacheti & De Mio (2008) presented SCPT test results from three relatively well documented tropical research sites (Bauru, São Carlos and Campinas) in the State of São Paulo, Brazil. SCPT data for the three sites were plotted on the Robertson et al (1995) and Schnaid et al (2004) chart, as shown in Figure 13. The interpretation of SCPT data indicated that the bonded structure of tropical soils produces G_o/q_c ratios that are systematically higher than those measured in cohesionless soils. It was also observed that lateritic soils achieve a higher G_o/q_c ratio than saprolitic soils. The high elastic stiffness and the low cone resistance at the surficial soil layers is caused by laterization process which enriches the soil with iron and aluminum and their associated oxides, the high concentration of oxides and hydroxides of iron and aluminum bonds support a highly porous structure. Relating an elastic stiffness to an ultimate strength is an interesting approach to help identify tropical soils since the low strain modulus from seismic tests reflects the weakly cemented structure of lateritic soils while the penetration brakes down all cementation (Schnaid et al. 2004; Viana da Fonseca & Coutinho, 2008).

In addition, recent research is focusing on the possibility of deriving the stiffness degradation laws of geo-materials and on penetration of partial drained effects in residual soils and tailing materials (e.g. Schnaid et al. 2004, Schnaid, 2005 and others).

New equipment development encompasses PETROBRAS / COPPE / UFRJ soil investigation equipment that consists of a piezocone installed at the tip of a torpedo-pile (Porto et al. 2010). The new equipment, named torpedo-piezocone, is able to measure cone resistance (q_c), sleeve friction (f_s), pore pressure at the cone face (u_1) and cone shoulder (u_2) as well as cone temperature during free-fall and after final penetration of the torpedo. Velocity, as well as displacement (depth) is obtained from accelerometer data, as in the case of the torpedo-pile.

As for future trends in the next 10 to 15 years, many engineering activities are expected in South America, with significant improvement in public infrastructure and private enterprises (buildings, industries, etc.). A continuous increase in the use of the CPT is expected, extending the experience on soft clays to residual and colluviums soils and other similar deposits. Geo-environmental applications, using the CPT, is likely to be a growing trend in the region.

Table 2. Comparative study – in situ tests correlations versus reference tests (modified from Coutinho, 2007; 2008)

PARA-METER	IN SITU CORRELATION	EQUATIONS	REFERENCE RESULTS	RECIFE EXPERIENCE	CORRELATION RECOMMENDED
OCR	DMT - Lunne et al. (1989)	$OCR = m K_D^{1.17}$; m = 0.3 - 0.33 (young clays: <60,000 years)	Oedometer (σ'_p for d_{24hour})	± 10 %	Lunne et al. (1989) ± 10 %
	DMT - Powell et al. (1988)	$OCR = 0.24 K_D^{1.32}$		± 15 %	
	VANE - Mayne e Mitchel (1988)	$OCR = 22 (IP)^{-048}(S_{uVANE} / \sigma'_{V0})$		± 16 %	Mayne & Mitchel (1988) ± 16 %
	CPTU - Lunne et al. (1989)	$OCR = f(\Delta u_1 / \sigma'_{V0})$		1.00 ± 0.24	Lunne et al. (1989) $OCR = f(\Delta u_1 / \sigma'_{V0})$ 1.00 ± 0.24
	CPTU - Lunne et al. (1989)	$OCR = f\{(q_t - \sigma_{V0)} / \sigma'_{V0}\}$		1.32 ± 0.16	
	CPTU -Kulhawy & Mayne (1990)	$\sigma'_p = 0.33 (q_T - \sigma_{V0})$		1.32 ± 0.19	
	CPTU -Sully et al. (1988), Sully & Campanela (1992)	$OCR = 0.49 + 1.5 (u_1 - u_2)$		1.39 ± 0.20	$\sigma'_p = 0.25 (q_t - \sigma_{v0})$ (preliminary proposal)
K_0	DMT - Lunne et al. (1990)	$K_0 = 0.34 K_D^{0,54}$ (young clays: < 60,000 years)	$K_0 = (1- \sin \Phi') OCR^{\sin\Phi'}$ (Mayne & Kulhawy, 1982)	± 10 %	Lunne et al. (1989) ± 10 %
	DMT -Marchetti (1980)	$K_0 = (K_D / 1,5)^{0.47} - 0,6$		40 % (higher)	
	CPTU - Sully & Campanella (1991)	$K_0 = 0.5 + 0.11(u_1 - u_2)/\sigma'_{vo}$		1.06 ± 0.24	Sully& Campanella (1991) 1.06 ± 0.24
	CPTU -Kulhawy & Mayne (1990)	$K_0 = 0.1Q = 0.1(q_T - \sigma_{V0} / \sigma'_{V0})$		1.21 ± 0.12	

Table 2 (cont). Comparative study – in situ tests correlations versus reference tests (modified from Coutinho, 2007; 2008)

PARA-METER	IN SITU CORRELATION	EQUATIONS	REFERENCE RESULTS	RECIFE EXPERIENCE	CORRELATION RECOMMENDED
Su	DMT -Marchetti (1980)	$Su = 0.22\ \sigma'_{V0}\ (0.5\ K_D)^{1.25}$	(Triaxial) UU-C / CIU - C	± 20 %	All correlation (see reference of Su)
			(Vane)	± 15 %	
	DMT - Lacasse & Lunne (1988)	$Su = 0.20\ \sigma'_{V0}\ (0.5\ K_D)^{1.25}$	(Triaxial) UU-C / CIU - C	± 15 %	
			(Vane)	± 18 %	
	PMT - Powell et al. (1990)	Su = PL* / 7.8	(Triaxial) UU-C / CIU - C	1.02 ± 0.17	
			(Vane)	1.14 ± 0.24	
	CPTU - Tavenas e Leroueil (1987)	$Su = (q_T - \sigma_{V0}) / N_{KT}$	$N_{KT} = 12 \pm 1.3$ (Vane)	± 15 %	
	CPTU - Lunne et al. (1989)	$Su = (u_2 - u_0) / N_{\Delta u}$	Triaxial UU-C / CIU - C	$N_{\Delta u}$ (range 7.5 to 11.0) (average 8.0 to 9.0)	
M	DMT - Marchetti (1980)	$M = R_M . E_D$; $R_M = 0.14 + 2.36 \log K_D$; $(I_D < 0.6)$	Oedometer	≤ 20 % (higher)	Marchetti (1980) ≤ 20 % (higher)

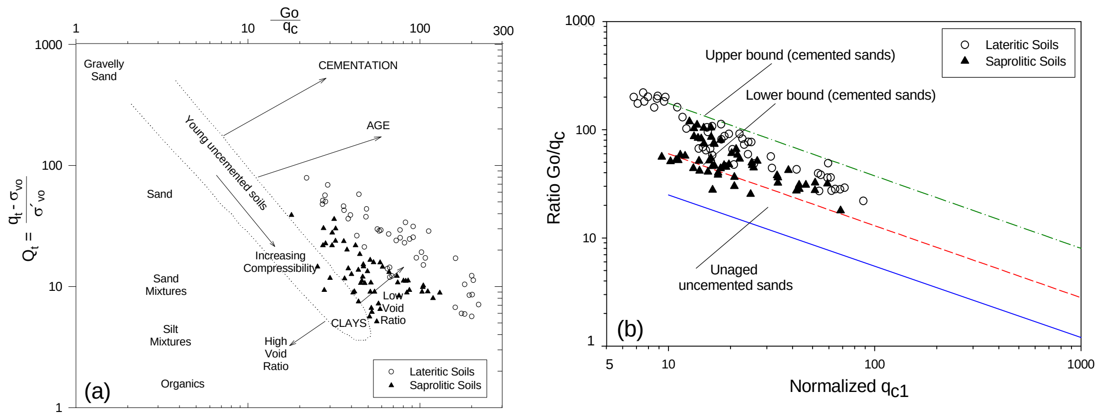


Figure 13. Relationship between Go and qc for three sites in Brazil: (a) Robertson et al (1995) chart (b) Schnaid et al (2004) chart (Viana da Fonseca & Coutinho, 2008, modified from Giacheti & De Mio, 2008)

8 SUMMARY

It is difficult to produce an overview of the site investigation practice in the South American continent, given to the unbalanced distribution of resources in the region. Reported information in the continent is mainly related to the electrical cone and piezocone. Combination of different techniques by coupling the cone robustness with additional information derived from other sensors (seismic cone, cone-pressuremeter, resistivity cone) is basically restricted to research environment. Whereas the SPT is the most dominant in situ testing technique in Brazil, the piezocone represents a fundamental part in almost every major infra-structure site investigation program located in regions where low bearing capacity soil formations prevail. Cone penetration tests are carried out by specialist site investigation contractors.

Universities have been given important contributions for the development and improvement of the test. Ground profile and assessment to design parameters are the most common applications in the region. Experience gained in clay deposits encouraged the use of the CPT in other applications comprising very soft organic peat, intermediate permeability silty soils, tailing deposits, some highly weathered residual soils among others. An increase in the CPT use is expected in the region.

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REFERENCES

ABNT. 1991. Ensaio de Penetração de Cone In Situ (CPT). *NBR 12069 (antiga MB3406), Associação Brasileira de Normas Técnicas.*

Almeida, M.S.S. 1998. Site characterization of a lacustrine very soft Rio de Janeiro orgânic clay, *Proc. Geotechnical site characterization, ISC'98, Atlanta*, Vol. 2, pp. 961-966.

Almeida, M.S.S., Marques, M.E.S., Baroni, M. 2010. Geotechnical parameters of very soft clays obtained with CPTu compared with other site investigation tools. *CPT'10, California*.

Almeida, M.S.S. & Marques, M.E.S. 2003. The behavior of Sarapuí soft clay. *Characterization and Engineering Properties of Natural Soils*. *Tan et al. eds., Balkema*, 1: 477-504.

Almeida, M.S.S., Danziger, F.A.B., Lunne, T. 1996. Use of the piezocone test to predict the axial capacity of driven and jacked piles in clay. *Canadian Geotechnical journal*, Vol. 33, 1, pp. 23-41.

Barata, F.E. 1983. Propriedades mecânicas dos solos – uma introdução ao projeto de fundações. *Livros Técnicos e Científicos Editora S.A., Rio de Janeiro.*

Barata, F.E., Danziger, F.A.B. 1995. The use og CPT to evaluate the settlements of shallow fundacions on residual soils. *Proc.,Int. Symp. on Cone Penetration testing, CPT'95, Linköping, swedn*, Vol. 2, pp. 393-398.

Bellotti, R., Ghionna, V.N., Jamiolkowski, M., Robertson, P.K. and Peterson, R,W. 1989. Interpretation of moduli from self-boring pressuremeter tests in sand, *Geotechnique*, 39(2): 269-292.

Cavalcante, E.H., Danziger, F. A. B., Giacheti, H. L., Coutinho, R.Q. and others. (2007). Campos esperimentais brasileiros. *Geotecnia*. N_0. 111, pp. 99-205.

Chen, B.S., Mayne, P.W. 1996. Statistical relationships between piezocone measurements and stress history of clays. *Canadian Geotechnical Journal*, Vol.33, pp 488-498.

Coutinho, R.Q. 2008. In situ tests in geotechnical practice and advances. Proc. *XIV Brazilian Congress on Soil Mechanics and Geotechnical Engineering, Búzios, RJ*, pp. 201–230.

Coutinho R. Q. 2007. Characterization and engineering properties of Recife soft clays. Characterization and Engineering Properties of Natural Soils. *Tan, Phoon, Higth and Leroueil (editors).* Taylor & Francis, p. 2049-2100.

Coutinho, R. Q.; Souza Neto, J. B.; Dourado, K.C.A. 2004. General Report: Characterization of non-textbook geomaterials. *Proc. ISC-2 on Geotechnical and Geophysical Site Characterization, Porto, Portugal*, Vol. 2 pp.1233-1257.

Coutinho, R.Q., Oliveira, J.T.R., Danziger, F.A.B. 1993. Caracterização geotécnica de uma argila mole do Recife. *Solos e Rocha*, Vol. 16, N_0. 4, pp. 255-266.

CPRM–Geological Survey of Brazil - *http://www.cprm.gov.br* - Geodiversity Map (1:2.5000.000) and Geological Map of Brazil to Millionth scale 1:1.000.000.

CPRM– Geological Survey of Brazil - *http://www.cprm.gov.br/publique/media/americasul.pdf* - Geological Map of South America.

Danziger, F.A. 2007. In situ testing of soft Brazilian soils. *Proc. of the 3rd International Seminar on Soil Design Parameters from In Situ and Laboratory Tests, Zbigniew Mlynarek* Ed., Poznan, 5-22.

Danziger, F.A.B., & Schnaid, F. 2000. Piezocone Tests: Procedures, recomendatios and interpretation (in Portuguese). *In: Anais do Seminário Brasileiro de Investigação de Campo, BIC - SEFE IV, 3, 1-51, São Paulo: ABMS.*

De Mio, G., Giacheti, H.L., Viana da Fonseca, A. and Ferreira, C. 2010. CPTU interpretation for stratigraphic logging: differences between sedimentary and residual soils. *CPT'10, California.*

Douglas, B.J. & Olsen, R.S. 1981. Soil classification using electric cone penetrometer, Cone Penetration Testing and Experience, *ASCE National Convention*, *St. Louis*, 209-227.

Duncan, J.M. & Buchignani. 1975. An engineering manual for settlement studies. *Department of Civil Engineering*, *University of California, Berkeley*.

Eslaamizaad, S. & Robertson, P.K. 1997. A Framework for In-situ determination of sand compressibility. *49 th Can. Geotech. Conf.; St Johns Newfoundland.*

Giacheti, H. L. & De Mio, G. 2008: Seismic cone tests in tropical soils and the Go/qc ratio. *Accepted to Proceedings of ISC'3.*

Houlsby, G.T. & Teh, C.I. 1988. Analysis of the piezocone in clay. *Proc. of the International Symposium on Penetration Testing, ISOPT-1, Orlando*, pp. 777–783.

ISSMFE. 1989. International reference test procedure for cone penetration test (CPT). *In Report of the ISSMFE Technical Committee on Penetration Testing of Soils – TC 16 with Reference Test Procedures CPT - SPT - DP - WST, SGI.*

Jamiolkowski, M., Ladd, C.C., Germaine, J.T. & Lancellotta, R. 1985. New developments in field and laboratory testing of soils. *11^{th} Int. Conf. on Soil Mech. Found. Eng., San Francisco*, 1: 57-153.

Juang, C.H., Yuan, H., Lee, D.H., and Lin, P.S. 2003. "Simplified CPT-based method for evaluating liquefaction potential of soils", *Journal of Geot.and Geoenv. Engineering 129*, No. 1, pp. 66-80.

Kulhawy, F.H. & Mayne, P.W. 1990. Manual of estimating soil properties for foundation design. *Geotech. Engng. Group, Cornell University, Ithaca.*

Lunne, T., Robertson, P.K. & Powell, J.J.M. 1997. Cone Penetration Testing in Geotechnical Practice, *Blackie Academic & Professional*, 312p.
Mayne, P.W. 1991. Determination of OCR in clays by piezocone tests using cavity expansion and critical state concepts. *Soil Foundations*, 31(1): 65-76.
Mayne, P.W. & Kulhawy, F.H. 1982. K_o-OCR relationships in soil. *Journal of Geotech. Engng*, 108(6): 851-872.
Mondelli, G., De Mio, G., Giacheti, H.L., and Howie, J.A. 2009. The use of slot filter in piezocone tests for site characterizacion of tropical soils. *17th International Conference on Soil Mechanics and Geotchnical Engineering.* Vol. 2, pp. 973-976.
Moss, R.E.S., Seed, R.B., Kayen, R.E., Stewart, J.P., Der Kiureghian, A., and Cetin, K.O. 2006. "CPT-based probabilistic and deterministic assessment of in situ seismic soil liquefaction potential, *Journal of Geotechnical and Geoenvironmental Engineering 132*, No. 8, pp. 1032 - 1051.
Porto, E. C., et al. 2010. The develolopment of the torpedo-piezocone. *Proc. of the ASME 2010 29th Int. Conf. on Ocean, Offshore and Arctic Engineering OMAE 2010, ASME, Shanghai*, pp. 1-10.
Powell, J.J.M & Butcher, A.P. 2004. Small strain stiffness assessments from in situ tests. 2nd Int. Conf. on Site Characterization, Milpress, Porto, 2:1717-1729.
Robertson, P.K. 1990. Soil classification using the cone penetration test. *Canadian Geot. Journal,* Vol. 27: 151-158.
Randolph, M. F. & Hope, S. 2004. Effect of cone velocity on cone resistance and excess pore pressures. *Proc. Int. Symp. on Engng. Practice and Performance of Soft Deposits. Osaka*.
Robertson, P.K. and Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test, *Canadian Geotechnical Journal*, 35: 442-459.
Robertson, P.K. & Campanella, R.G. 1983. Intepretation of cone penetration tests. *Canadian Geotechnical Journal*. 20(4): 734-745.
Robertson, P.K., Campanella, R.J., Gillespie D, and Grieg, J. 1986. Use of piezometer cone data. *Proc. In-Situ '86, ASCE Specialty Conference on the Use of In Situ Tests in Geotechnical Engineering, Blacksburg, VA, ASCE Specialty Geotechnical Publication* 6, 1263–1298.
Robertson, P.K., Sasitharan, S., Cunning, J.C. & Segs, D.C. 1995. Shear wave velocity to evaluate flow liquefaction. *J. Geotechnical Engineering, ASCE, 121*(3), pp.262-73.
Rocha Filho, P. & Schnaid, F. 1995. Cone penetration testing in Brazil, National Report. *Proc., Int. Symp. On Cone Penetration Testing, CPT'95, Linköping, Sweden*, Vol. 1, pp. 29-44.
Schmertmann, J.H. 1978. Guidelines for cone penetration test, performance and design, *US Federal Highway Administration, Washington, DC, Report FHW-TS-78-209.*
Schnaid, F. 2009. In Situ Testing in Geomechanics. *Oxon: Taylor and Francis.*
Schnaid, F. 2008. Investigação Geotécnica em Maciços Naturais não-convencionais. *Proc XIIV GEO, Congresso Luso-Brasileiro de Geotecnia, Coimbra, Portugal*, pp. 17-40.
Schnaid, F. 2005. Geo-characterisation and properties of natural soils by in situ tests. *Keynote Lecture. 16th ICSMGE, Osaka*, (1), 3-45. Millpress, Rotterdam.
Schnaid, F., Fahey, M. and Lehane, B. 2004. In situ test characterisation of unusual geomaterial. Keynote Lecture. *Geotechnical & Geophysical Site Characterization*. Ed. A. Viana da Fonseca e P.W.Mayne. Vol, pp. 49-74. Millpress, Rotterdam.
Schnaid F., Sills G.C., Soares J.M.D., Nyirenda Z. 1997. Predictions of the coefficient of consolidation from piezocone tests, *Canadian Geotchnical Journal*, Vol. 34, No. 2, PP. 143-159.
Schnaider, J.A., Lehane, B.M. and Schnaid, F. 2007.Velocity effects on piezocone measurements in normally and overconsolidated clays. *Int. J. Physical Modelling in Geotechnics*, 7(2): 23-34.
Senneset, K. & Janbu, N. 1985. Shear strength parameters obtained from static penetration tests, *Symp. Shear Strength of Marine Sediments, San Diego, ASTM Special Tech. Pub., STP 883*, 41-54.
Soares M.M.D. 1996. A study of the behaviour of the CEASA soft clay deposit (in portuguese), *D.Sc. Thesis, Federal University of Rio Grande do Sul, Porto Alegre.*
Tanaka, H., Tanaka, M. & Iguchi, H. 1994. Shear modulus of soft clay measured by various kinds of tests. *Proc. Symp. on Pre-Failure Deformation of Geomaterials, Sapporo*, 1: 235-240.
Teh, C.I. & Houlsby, G.T. 1991. An analytical study of the cone penetration test in clay. *Géotechnique,* 41(1): 17-34.
Viana da Fonseca, A. & Coutinho, R.Q. 2008. Characterization of residual soils. *Geotechnical and Geophisical Site Characterization* – Huang & Mayne (Eds), London,UK, PP. 195-248.
Wang, W. 1979. Some findings in soil liquefaction. *Water Conservancy and Hydroelectric Power Scientific Research Institue, Beijing, China*.Yu, H.S. 2004.