Resistivity Piezocone in the Conceptual Site Model Definition

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Abstract. The management and remediation of contaminated sites are strongly dependent on the diagnosis process during the site characterization program. A Conceptual Site Model (CSM) elaborated by use of high-resolution site characterization (HRSC) tools allows for a detailed diagnosis of geo-environmental issues. The piezocone (CPTu) test is a high-resolution tool that allows several specific sensors to be attached, such as the resistivity module. This hybrid device is called the resistivity piezocone (RCPTu). A simulated geo-environmental site characterization program was performed on a Brazilian erosion site using several tools (direct-push soil samplers, hollow stem auger and RCPTu) to develop the CSM for a site similar to the Brazilian conditions. The aim was to elaborate a detailed stratigraphical profile and verify the applicability of this tool at the studied site. It was noted that the RCPTu data interpretation was consistent with the data from traditional methods, with much more details. Better results were achieved when decision-making occurred on site. It was concluded that the RCPTu is a very useful tool in elaborating a suitable hydrogeological conceptual site model, even for Brazilian conditions, especially in an approach that prioritizes high-resolution geo-environmental characterization.

Keywords: site characterization, in situ testing, stratigraphical logging, soil sampling, RCPTu.

1. Introduction

A deficient site characterization program is the major cause of inadequate remediation of contaminated sites. It has been noted, in several cases, that it fails at the very first step, when the site diagnosis is elaborated or, more precisely, during Conceptual Site Model (CSM) development.

In Brazil, efforts aimed at proper geo-environmental site characterization are still in an early phase. Two major legal instruments were recently published: CETESB - The São Paulo State Law # 13577/2009 and the CONAMA - The Federal Resolution # 420/2009, valid throughout the Brazilian territory.

The person or company that caused the contamination, or earned financial gain through it, or the site owner is liable for the remediation of a contaminated site in Brazil. They have the legal obligation to investigate and to recover the site. The “Legally Responsible Person” currently hires a “Technical Manager” to do the job. This manager subcontracts certain outsourced services (chemical analysis laboratories, drilling companies, soil, groundwater and vapor sampling, monitoring well installations, among others) trying to optimize project-cost reduction. Typically, this manager just strictly complies with the Brazilian requirements. In most cases, the site is not properly characterized; therefore, it is not suitably remediated.

The goal of the “Legally Responsible Person” in the U.S. approach (USEPA, 2004) is to rehabilitate the site as effectively as possible, considering the project globally. Significant investments have been made in research and technologies, tools and equipment for site assessment, investigation and diagnosis of contaminated sites to achieve this goal.

A number of North American companies implemented the Triad Approach and Expedite Site Assessment to achieve this goal, based on three basic principles:

- Prompt and on-site decision-making;
- The CSM must be continuously reviewed and, at the end of the diagnostic job on site, it should have the lowest possible degree of uncertainties, which must be manageable (Aquino Neto, 2009; Killinbeck, 2012; Quinnan, 2012);
- Dense and high-resolution data must be collected within a short timeframe (Cleary, 2009; Martin & St Germain, 2008).

The piezocone (CPTu) and the resistivity piezocone (RCPTu) and their accessories are frequently used for the characterization of contaminated sites in the U.S. (Vienken et al., 2012). They are very useful tools since:

- They collect a high density of data very quickly (Lee et al., 2008; Killinbeck, 2012; Welty, 2012);
- They provide a high resolution profile at relatively low cost (Giacheti et al., 2006; De Mio & Giacheti, 2007, Lee et al., 2008; Quinnan, 2012; Shinn III, 2004);
- Decision-making can occur on site;
- It provides a very good understanding of the geology, a most critical variable in CSM elaboration (Cleary, 1989; Killinbeck, 2012; Quinnan, 2012; Welty, 2012);
- They provide the development of a very good hydrostratigraphical profile (Cleary, 2009; Quinnan et al., 2010; Vienken et al., 2012);
• They allow soil and groundwater data to be collected, which would be very difficult (or impossible) to obtain in certain specific sites.

Site characterization campaigns were currently carried out to assess contaminated sites in regular jobs in Brazil to follow an outdated approach. They end up incomplete and raise many uncertainties. Reasons that contribute to this are the fact that decisions are not made on site and the traditional site characterization methods use low-resolution tools. In addition, traditional methods are usually not adequately employed, resulting in inefficient remediation projects with extremely long periods and at very high costs for the “Legally Responsible Person” and for society as a whole, often making it impossible to properly revitalize the site.

A case study is presented where RCPTu were used as the major tool to simulate proper site characterization with a low degree of uncertainty, as should be done in a contaminated site following the US EPA approach. The objective is to develop a solid CSM in a simulated geo-environmental site characterization and discuss the advantages and limitations of this approach in terms of our current conditions in Brazil.

2. Studied Site

The studied site is an erosion process in the city of Bauru, in the central region of São Paulo State, Brazil. The city is settled in a natural amphitheater with a radius of about 5 km, modeled by several streams at the headwaters of the Bauru River. The regional relief presents wide and gentle hills, and the rocks are sandstones of the Marília and Adamantina Formations. The typical soils are residual from sandstone of the Marília, Adamantina and Cenozoic Formations, with a sandy texture and small portion of clay. Soil formation in tropical climates, marked by the alternation of rainy seasons and droughts, intensifies leaching in the thin surface horizon, producing a porous and permeable structure, usually with a deep groundwater table.

This erosion process is located nearby the São Paulo State University (Unesp) campus and along the Água Comprida Creek (Fig. 1). It originated from the collapse of the rainwater dissipation system, poor design, poor construction and lack of infrastructure and maintenance, as described by Ide et al. (2010). The process reached a huge dimension with the installation of land allotment for housing (the residential condominiums Jardim Colonial and Jardim Niceia) in an area highly susceptible to erosion.

The rapid evolution of the erosion process was due to several heavy rainfalls, typical in this region, which struck and destroyed the water dissipating system. Figure 2 shows one of the branches of the erosion process in the studied site. According to Ide et al. (2010), a revitalization project was elaborated to rectify the bed of the stream due to the rapid evolution of the erosion process. However, the lack of maintenance is contributing to slope instability, and minor erosions are still taking place at the site.

Several site characterization campaigns, including field observation, laboratory and in situ tests were carried out at the site to better understand and explain the erosion process (Campos, 2014; Ide et al., 2010).

3. Site Characterization

Ide (2009) previously carried out five SPT at the studied site. They were used to elaborate a preliminary Conceptual Site Model (CSM). After this, soil sampling, four monitoring well installation using the hollow stem auger drilling and ten resistivity piezocone tests were carried out at the site by Riyis (2012) to simulate proper site characterization as it should be undertaken in a contaminated site, following the US EPA approach.

3.1. Soil sampling

Soil samples were collected using the single tube direct-push soil sampler (DPT) at 9 locations every 1 m depth interval. It consists of a pushing tubular steel sampler, 1.40 m-long, with a 55 mm outer diameter and 46 mm inner diameter. This sampler contains a liner (1.20 m-long with an outer diameter of 44 mm), a transparent polymer (HDPE or PVC) tube with soil samples retrieved and stored after spiking and removing the set of direct-push tools.

The DPT (Fig. 3) was pushed into the ground using percussion. The equipment was an SB-50 Atlas Copco hydraulic hammer coupled to a truck-mounted hydraulic rig. Besides the sampler, the DPT has extending rods and adapters. Once the pushing process is complete, the DPT is retrieved and the liner is removed and sealed with two HDPE plastic caps. The DPT is reassembled and replaced in the borehole, with an extending rod to sample 1.0 m deeper, as represented in Fig. 3.

The choice for a single tube, direct-push soil sampler rather than another type, like the dual tube or the piston sampler, was made because it is faster and more widely used in Brazil. The other two types are only used in Brazil in exceptional cases (Riyis, 2012).

In cases where the borehole collapses, casing is necessary. In such cases, soil sampling is carried out with hollow stem auger (HSA) drilling. In the present study, the HSA tools were installed using a rig mounted on a VW 9150 truck. This equipment allows for the application of a maximum torque of 5 kN.m.

The DPT set is pushed into the ground and then removed and dismantled and the liner is removed from inside the sampler for tactile-visual soil identification. Then, HSA drilling is carried out to the previous sample depth. When this depth is reached, the DPT set inside the HSA is taken out and the DPT is replaced with a direct-push soil sampler inside the hollow boreholes. The DPT is hammered one more meter, and the sampling procedure is repeated (Fig. 4).
3.2. RCPTu

The piezocone is an instrumented probe that is pushed into the ground vertically at a standard rate of 20 mm/s. Measurements of tip resistance ($q_t$), sleeve friction ($f_s$) and pore pressure ($u$) at up to three locations are typically recorded every 10, 20, 25 or 50 mm depth intervals.

Due to the “inner” geometry of a cone penetrometer the ambient pore water pressure will act on the shoulder area behind the cone and on the ends of the friction sleeve, and this effect is often referred as “the unequal area effect” ($a$) and influences the total stress determined from the cone and friction sleeve (Lunne et al., 1997). The corrected cone resistance ($q_{tc}$) is given by Eq. 1:

$$q_{tc} = q_t + u_s(1 - a)$$

Changes in the friction ratio ($R_f = f_s / q_t \cdot 100\%$) are often used to identify changes in the soil profile based on soil behavior classification charts. Pore pressure records provide information about the response of the ground to the probe during the pushing and the consequent migration of fluids. A pressure transducer inside the piezocone takes the pore pressure measurement. The traditional procedure to

Figure 1 - Site location and aerial view of the studied site (adapted from Google Maps).
measure pore pressure is by saturating the porous element with water or glycerin. Larsson (1995) and Elmgren (1995) suggested the use of a slot filter filled with grease as an alternative procedure.

The slot filter filled with grease is easier to prepare and handle than the porous piezo-element saturated with glycerin. It has a better application for deep groundwater level (Mondelli et al., 2009). Mondelli et al. (2010) have used this technique in tropical soils. The pore pressure transducer inside the piezocone is brought into stiff contact with the pore water in the soil by filling the inner cavity with water and pressing the grease into the cavities inside the cone tip.

The RCPTu is like any other CPTu. The additional procedure is to add a signal generator to the data acquisition system to control the current level and frequency for the electrical bulk soil resistivity (or conductivity) measurements.

The used CPTu probe was produced by Geotech AB (Sweden), NOVA acoustic model (wireless). The position to measure pore pressure is standard (u) and according to international practice. A slot filter filled with grease was used to measure pore pressure. The equipment has a ratio of unequal areas (a) equal to 0.84. This hybrid probe has a resistivity (or conductivity) module, which was also produced by Geotech AB. This module provides bulk soil resistivity data, also using the NOVA acoustic wireless system. Wireless data transfer and acquisition were performed with a microphone, which is part of this system.

The pushing equipment was anchored using double helicoids of 180 mm in diameter and extended rods with square coupling. Ten RCPTu were carried out using a hydraulic system attached to a tractor to perform the test.

The CPTu procedure followed the Brazilian Standards (ABNT-MB 3406/1990), like the ASTM D3441 standard. The hydraulic system was positioned, leveled and

Figure 2 - A branch of the erosion process (Ide et al., 2010).
anchored (Fig. 6). Next, the baseline was taken and the RCPTu was carried out at a constant rate, interrupted only to connect extra rods.

The data were recorded at regular 20 mm depth intervals and displayed in real time on a computer connected to an acoustic data transmission system. Thus, the following data were recorded: tip resistance ($q_t$), lateral friction ($f_s$), pore pressure ($u_2$) and bulk soil resistivity ($\rho_b$).

The piezocone data interpretation for stratigraphical logging can be done using a classification chart as the one proposed by Robertson et al. (1986), which correlates the corrected point resistance ($q^c$) and the friction ratio ($R_f$), as presented in Fig. 7.

Besides the soil classification, this chart also shows the tendency of variation for relative density ($D_r$), stress history ($OCR$), sensitivity ($S_t$) and void ratio ($e$). The piezocone also allows classifying the soil based on the pore pressure data, by using the pore pressure index ($B_p$), whose formula is presented inside the $B_{p}$ vs. $q_t$ chart from Fig. 7. This approach is best applicable in soft soils, where the point resistance is low and the generated pore pressure is usually high. As discussed by Lunne et al. (1997), the classification charts do not classify the soil based on the grain size distribution or plasticity but they provide an information about the soil behavior.

Recently Robertson (2009) updated the Unified Approach, in which the soil is classified based on the $I_v$ index calculated by Eq. 2 for qualitative analysis of the soil behavior. The soil behavior type (SBT) is function of a range of $I_v$ values and the position in the proposed classification chart. The interpretation of CPT data via this specific approach considers the soil in terms of its behavior. For example, it is not appropriate to say that a soil is a sand, but that behaves in the same way as a sand-like material.

$$I_v = \left(3.47 - \log Q_m\right)^2 + (\log F_r + 1.22)^2 \right)^{0.5}$$

(2)

where:

$$Q_m = \left(\frac{q_t - \sigma_w}{\sigma_w}\right) \times \left(\frac{p_{eq}}{\sigma_{w}}\right)^{0.3}$$

(3)

$$F_r = \left(\frac{f_s}{q_t - \sigma_w}\right) \times 100\%$$

(4)

$q_t$ = CPT corrected total cone resistance
\[ f_s = \text{CPT sleeve friction} \]
\[ \sigma_v = \text{pre-insertion in-situ total vertical stress} \]
\[ \sigma'_w = \text{pre-insertion in-situ effective vertical stress} \]

\[ \frac{(q_t - \sigma_v)}{p_a} = \text{dimensionless net cone resistance, and,} \]
\[ \frac{p_a}{\sigma_v} f = \text{stress normalization factor} \]
\[ n = \text{stress exponent that varies with SBT} \]
\[ p_a = \text{atmospheric pressure in same units as } q_t, \sigma_v, \text{and } \sigma'_w \]

**Figure 6** - Pushing rig and the RCPTu probe highlighted in the figure ready for the test.

**Figure 7** - Soil classification chart for CPTu interpretation proposed by Robertson et al. (1986).

| SBT  | Soil behavior type               |
|------|----------------------------------|
| 1    | Sensitive fine grained           |
| 2    | Organic material                 |
| 3    | Clay                             |
| 4    | Silty clay to clay               |
| 5    | Clayey silt to silty clay        |
| 6    | Sandy silt to clayey silt        |
| 7    | Silty sand to sandy silt         |
| 8    | Sand to silty sand               |
| 9    | Sand                             |
| 10   | Gravelly sand to sand            |
| 11   | Very stiff fine grained*         |
| 12   | Sand to clayey sand*             |

* Overconsolidated or cemented

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The hydraulic conductivity \( k \) profile is an interesting information for a proper hydro-stratigraphical interpretation, which is very useful for the geo-environmental site characterization. Robertson (2010) proposed relationships between soil permeability \( k \) and \( I_c \) represented by:

\[
k = 10^{(0.052 - 3.04I_c)} \text{ m/s for } 1.00 < I_c \leq 3.27 \tag{5}
\]

\[
k = 10^{(-4.32 - 1.37I_c)} \text{ m/s for } 3.27 < I_c < 4.00 \tag{6}
\]

Robertson (2010) says that the Eq. 5 and Eq. 6 can be used to provide an approximate estimate of soil permeability \( k \) and to show the variation of soil permeability with depth from a CPT sounding. The author also states that the normalized CPT parameters \( Q_n \) and \( F_r \) respond to the mechanical behavior of the soil and depend on many soil variables; the suggested relationship between \( k \) and \( I_c \) is approximate and should only be used as a guide.

4. Testing Data and Discussion

4.1. Previous data

Five SPT carried out on the studied site by Ide (2010) were used for site characterization of the erosion process to establish the preliminary CSM represented in Fig. 8. Based on this information, a predominantly heterogeneous sandy soil profile was expected. Presence of clayey lenses or other fine materials with diverse thickness at various locations of the soil profile could be typical at the site. The expected groundwater level was shallow (between 4 to 5 m depth), indicating the presence of several layers with different hydraulic conductivities.

According to this preliminary model, a free aquifer was predominantly associated to a sandy formation with high hydraulic conductivity. It formed the preferential flow for eventual contamination. Another important aquifer could be found close to the bedrock (expected at 12 to 15 m depth), confined by one or more aquitard layers with unknown thicknesses. This confined aquifer may also have a high hydraulic conductivity. Some vertical flow was also expected, demonstrating that there are, in fact, different aquifers. There were several uncertainties associated to this preliminary model since the SPTs were far away from one another (around 75 m) for the scale to which the appropriate CSM was intended to be defined.

![Figure 8](image-url) - Preliminary CSM interpreted for the studied site based on SPT data from Ide (2010).
4.2. Soil sampling

A site investigation campaign started with soil sampling with DPT, a technique recommended by US EPA and, in São Paulo State, by State Basic Sanitation Engineering Company (CETESB). It has been recognized as the best technique for soil sampling for contaminated site investigations (CETESB, 1999). A single tube was chosen as the DPT type for an initial sampling strategy. A cross section parallel to the creek and perpendicular to the direction of the studied site was established by Ide et al. (2010) to identify the site stratigraphical profile. In this section, 20 m distance was established between each sampling point as the default for the initial data collection (Fig. 9).

Ten soil-sampling points (DP-01 to DP-10) were taken with the single tube DPT. The samples were collected in liners at depth intervals of one meter, and they were described on site by the visual-tactile identification method.

Certain limitations were noted during sampling when attempting to establish an accurate CSM with the required resolution for proper characterization of this site. They were: collapse of the borehole wall requiring the use of casing; the hydraulic pressure loading material into the casing; and recovery of saturated sandy soil samples. These limitations are discussed as follow.

4.2.1. Borehole wall collapse

The collapse of the borehole wall occurred at the first sample point (DP-01). After retrieving the fifth sample (from 4.0 to 5.0 m depth), when the DPT was relocated into the borehole, it was noticed that the bottom of the sampling pit was about 4.7 m depth, instead of 5.0 m as expected. This means that at least 0.3 m of material fell to the bottom of the borehole and the following sample, which would be 5.0 to 6.0 m depth, was contaminated with material that did not belong to this layer. As such, the following two samples (5.0 to 6.0 and 6.0 to 7.0 m depth) were collected this way, and the soil from the bottom part of the liner was discharged.

The same procedure was adopted at the sample point DP-05; however, due to the need for extra information at this site location, the sample was recollected; i.e., after collecting the sample from 5.0 to 6.0 m depth, the DPT was taken out, and the probe was inserted once again, 1 m away from the previous one. HSA rotary drilling was used up to a 5.0 m depth and then soil sampling from 5.0 to 6.0 m was performed inside the hollow augers. After sampling, HSA drilling was continued up to a depth of 6.0 m, and the soil sample was collected inside the hollow auger for the depth from 6.0 to 7.0 m. When the sample from 5.0 to 6.0 m depth was recollected, a layer of about 0.2 m of plastic gray clay with sand grains was noted, which had not been detected in the previous sampling (with no casing). This was certainly due to contamination of the sample material from the upper layers. The procedure was repeated up to 8.0 m depth, but the samples below 6.0 m depth were not representative due to another factor: the hydraulic pressure have loaded material into the hollow augers, which will be discussed below.

4.2.2. Hydraulic pressure

Some samples were not representative due to sample contamination with material beneath the casing caused by the hollow augers, as previously described. The material inlet occurs because of the hydraulic pressure associated with friable and non-cohesive soils (fine sand characteristics). If the hydrostatic pressure is high enough (estimated to be 30 kPa), the soil tends to enter in the hollow augers and block the retrieval of representative samples. There are tools to minimize this problem, like the Piston Sampler from AMS Inc., for example. However, they were not widely available in Brazil in 2012.

4.2.3. Recovering samples

Another problem occurred during the sampling at the point DP-06: excessive volumes of water in the sandy soil sample. Consequently, the sampler penetrated the ground with casing (HSA), but when it was removed from the bore-

Figure 9 - DPT and RCPTu locations at the studied site.
hole, there was almost no recovered sample because it escaped from the DPT sampler due to the large amount of water coming out of it. There are other tools to minimize this effect, like the core catcher. Unfortunately, it was not used in Brazil in 2012.

4.2.4. Discussion

The soil profile interpreted via samples collected with the DPT at each investigation point is shown in Fig. 10. The refined CSM elaborated based on this information is represented in Fig. 11.

During the DPT data interpolation to elaborate the cross section presented on Fig. 11, it was decided to consider the Clayed Fine Sand and Silty Fine Sand just as a Fine Sand because it is very difficult to distinguish these soil types on site by tactile-visual identification. It was also considered during the interpolation process that there was no substantial difference in terms of flux and storage zones for both soils and they were defined as aquifers.

The three factors previously discussed restricted the elaboration of refined CSM in the vertical direction using just the DPT data. On the other hand, just the five SPT from Ide (2010) provided more information below a 6.0 m depth than DPT. The DPT data provided a more detailed soil profile at the shallow depths, where the free aquifer was expected and a better conceptual model at the horizontal direction was elaborated.

It is also clear that the CSM elaborated using the DPT leads to several uncertainties. They arose mainly from the limitation of data collection as well as the limitations in how to interpret the data, since tactile-visual soil identification depends on the technician who is performing it. Variations of two orders of magnitude are usual (Ahlers, 2012) and the scale on which samples can be described is inappropriate to identify the necessary differences in hydraulic conductivity.

4.3. RCPTu

RCPTu was carried out as the next step for CSM elaboration on the studied site. The goals of using this tool were:

- to define detailed profiles at the selected key site locations;
- to refine the CSM;
- to check the accuracy and limitations of this tool compared to the SPT and DPT;
- to perform a detailed check of the position at the soil profile for any minimal lenses of clay that may act as an aquitard; and
- to confirm the presence of a deeper aquifer.

Ten RCPTu were carried out at the same section where the soil samples were collected (Fig. 9), most of them right beside the DPT. The RCPT-04 was not used since it presented some communication problems between the probe and the data acquisition system probably caused by low battery at the very beginning of the test. The same happened during the RCPT-08 when it reached 4.72 m depth. After changing the batteries, a new test (RCPT-09) was carried out at the same position. So the interpretation logging for this point was identified as RCPT-08/09 up to 9.58 m depth.

![Figure 10](resistivity-piezocone-conceptual-site-model-definition.png)

**Figure 10** - Interpretation of all DPT logging from one of the longitudinal cross sections for the studied site.
A typical RCPTu data and the interpreted stratigraphical profile is presented in Fig. 12 for the RCPT-02. The identification of the soil profile is presented on the laptop screen during the test, allowing for refining the CSM right after every test. The soil type was identified by using Robertson et al. (1986) classification chart as a reference. They were confirmed and adjusted based on the samples retrieved with the DPT. Of note is the fact of how well the resistivity sensor complements the piezocone data ($q_t$, $f_s$ and $u$), and it provides information more suited to the scale that investigation of a contaminated site needs. In the studied site, the soil bulk resistivity ($\rho_b$) profile was also useful to help define the groundwater level (GWL) with a big drop on the $\rho_b$ value at 3.8 m depth (Fig. 12). This information was confirmed by the monitoring well installed beside this test location. It was also observed that variation in bulk resistivity ($\rho_b$) occurred together with the other variations on three CPTu parameters ($q_t$, $f_s$ and $u$) as the soil behavior changed (higher $\rho_b$ in sandy lenses and lower $\rho_b$ in clayey lenses), indicating that there is no sign of contamination on the studied site, since the $\rho_b$ value is much affected by the fluid present in the pores of soil. This is one of the main applications of the resistivity data.

Since the bulk resistivity ($\rho_b$) data is more affected by the fluid present in the pores of soil, which can be contaminated, this extra information is quite important for environmental site characterization using the piezocone technology, as discussed by Lunne et al. (1977). Daniel et al. (2003) discuss the applicability of resistivity piezocone for site characterization and they state that the RCPTu has proven to be a simple and useful screening tool mainly for delineating plumes of contaminated groundwater. De Mio et al. (2005) also illustrate the advantage of using the RCPTu to detect saltwater intrusion into a surficial sedimentary aquifer at the Paranaguá harbor, Paraná State, in Brazil. According to these authors, a high chloride concentration contaminated shallow water wells to supply water for local industries. Figure 13 shows two RCPTu of the tests carried out at the site guided by the dipole-dipole electrical profiling. One test (RCPTu B) intercepted the salt intrusion zone between 5.0 and 8.0 m depth. The other (RCPTu A) was positioned at a location with no evidence of contamination to get the $\rho_b$ background values. This example points out the advantage of using this hybrid test to detect contaminated groundwater as well as to select the target for water sampling.

Performing the data interpretation for the studied site, it is was confirmed that the RCPTu provided much more details in the vertical direction and presented far fewer limitations than the DPT, as shown in Fig. 10 (for DPT) and Fig. 14 (for RCPTu). The interpretation of each RCPTu logging profile considers Robertson et al. (1986) chart to-

![Figure 11 - Refined CSM for one cross section based on the DPT logging profiles.](image-url)
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Figure 12 - Typical resistivity piezocone data (RCPT-02) and soil profile identified with Robertson et al. (1986) classification chart and hydro-stratigraphical profile considering estimated $k$ profile.

Figure 13 - Two resistivity piezocones (RCPTu A and RCPTu B) and the soil profile identified with Robertson et al. (1986) classification chart in a site with salt intrusion into the groundwater (adapted from De Mio et al., 2005).
gether with the resistivity profile, as represented in Fig. 12. For each testing position, interpreted soil logging provided a better representation of soil variability in a more appropriate resolution for geo-environmental applications. It is also important to point out that these tests reached a greater depth than DPT, with great precision and high repeatability. Based on these test data, it was clearly possible to observe the existence of clayey and sandy lenses with variable thickness in all test points, and there is certainly a confined aquifer at the lower portion of the soil profile.

After the interpretation of all the RCPTu data and considering the position of each test, it was possible to refine the CSM previously presented. The cross-section profile is represented in Fig. 15.

It is also important to point out that the refined CSM based on RCPTu data showed the detection of some clayey (or fine material) and some sandy (or coarser material) lenses, and permitted the identification of the storage and flux zones following the approach suggested by Quinan et al. (2010) and Quinan (2012). The estimated $k$ profile calculated based on the CPTu data (Eq. 5 and Eq. 6), as suggested by Robertson (2010) was used and it was useful to help identifying clayey lenses (storage zones), as shown in Fig. 12 in a detailed interpretation of the RCPT-02 test. All these lenses were detected by the four ($q_r$, $f_r$, $u$ and $p_c$) RCPTu sensors. The elaboration of a figure like this is the first step in the interpretation of the hydro-stratigraphical profile, and it can be conducted on site. A closer look at the hydrogeological heterogeneities on a detailed scale revealed the presence of several storage zones, and two major layers: an important flux zone and an important store zone, as shown in Fig. 12. These heterogeneities are very important to CSM elaboration and to future remediation projects on a site, as discussed by Welty (2012) and Cleary (2009).

The CSM was significantly improved on site after the RCPTu campaign. It was also possible to define the exact position of the monitoring wells sampling screens. The position of the monitoring well sampling screen for the studied site would be the important flux zone with a window size equal to the thickness of the important flux zone indicated in Fig. 12. This procedure is carried out as the next step of geo-environmental site characterization.

The installation of monitoring wells is considered the best approach in Brazil for conducting hydrogeological site characterization. It must be preceded by a consistent CSM with the highest accuracy, resolution and detail as possible. If a consistent CSM does not exist, and the only information is the drilling itself for well installation, the uncertainties associated with the installation process, and the region where this well is effectively monitored, become so questionable that they can derail any accurate decision.

The major limitation of the RCPTu and all pushing accessories is the fact that their penetration is difficult at sites with dense soils, large boulders, rock or cemented layers. Another limitation in countries like Brazil is that the equipment used by the local contractors is imported. It makes the purchase, maintenance, calibration and repairing more expensive and time consuming.
5. Conclusions

The interpretation of RCPTu data was consistent for refining the conceptual site model elaboration at the studied site. This test can be used in an analogous way to the traditional ones (direct-push sampling and hollow stem auger drilling) since the achieved results were at least equivalent. They were faster and provided a greater level of detail than the traditional method. Geological and hydrogeological heterogeneities were detected within centimeter accuracy, which is not possible with DPT sampling and monitoring well installation.

The RCPTu presented fewer limitations than the traditional methods in the studied site, chiefly so when compared to the DPT. They reached greater depths and were more reliable, especially in cases where DPT presented limitations.

The bulk resistivity ($\rho_b$) complemented $q_t$, $f$, and $u$ data and it was useful to detail the stratigraphical profile and to help define the groundwater level for the studied site. The RCPTu data for delineating plumes of contaminated groundwater, as presented by De Mio et al. (2005), is not applicable in the studied site since there was no sign of contamination.

The RCPTu was a very useful tool to elaborate a suitable hydro-stratigraphical conceptual site model, especially in an approach that prioritizes high-density data collection in a high-resolution site investigation. The data were more consistent, and this hybrid tool was very useful in supporting a proper site investigation and diagnosis. It was also observed that site investigation achieves a better result when decision-making is made in real time, on site.

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