Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1809

Energy-based interpretation of the Dynamic Probing Light (DPL) in two Experimental Research Sites

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ABSTRACT: In situ tests are interesting in site investigation as they can assess large volumes of soil and be quickly carried out. Among the different in situ tests are the dynamic probing tests (DP), especially the dynamic probing light (DPL), a compact device with low penetration energy, that is sensitive to small variations that may occur along the site profile, variations that are not always possible to record using tests with higher energies, such as the SPT and the heavy and super heavy dynamic probing tests (DPH and DPSH). Combined with its good repeatability, the DPL can be used in the preliminary site characterization of tropical soils. The instrumentation of the rods also allows the definition of the system's efficiency, allowing the interpretation of the test data in terms of energy, using a rational approach. The rational interpretation of dynamic tests allows the definition of a unit tip resistance, q_p, and a unit friction resistance τ_l, that can be compared to the CPT tip resistance, q_c, and friction resistance, f_s. This paper presents comparisons of q_p and τ_l with q_c and f_s in two well-documented unsaturated tropical soil sites in State of São Paulo, Brazil using the rational interpretation of the DPL data. CPTs and DPLs were carried out about 8 m depth at both sites. The q_p profiles were analogous to the q_c profiles for both sites considering the energy-based interpretation. For the τ_l profiles, a site dependent empirical factor to overcome the scale effect had to be introduced to obtain an analogous profile to f_s. Using the rational interpretation and the empirical factor introduced, the rationally interpretated DPL profiles were analogous to the CPT profiles, highlighting the use of DPL as a tool for in situ site characterization, including sites with unsaturated tropical soil profiles.

KEYWORDS: Site characterization, DPL, CPT, Rational interpretation.

1 INTRODUCTION

Site investigation is an extremely important stage in geotechnical design. The use of in situ tests allows the definition of the site profile and an estimate of mechanical parameters (Giacheti & Queiroz 2004). There are several techniques of site investigation, as the Standard Penetration Test (SPT), Cone and Piezocone Penetration Test (CPT and CPTu), Flat Dilatometer Test (DMT), Menard Pressuremeter Test (PMT), and geophysical techniques (Robertson 1986, 2016). However, these techniques are expensive, require skilled operators and specific equipment.

The Dynamic Probing Light (DPL) is an interesting investigation technique, as it is a compact equipment that can access sites where conventional sounding equipment may have some restrictions, areas where heavy vehicles cannot access and even slopes (Dos Santos and Bicalho 2017; Arabpour Roghabadi et al. 2021; Almeida et al. 2024; Kotini et al. 2025; Herrera et al. 2025).

It is predominantly used in preliminary site investigations to obtain correlations with other in situ tests (Mohammadi et al. 2008; Hashemi and Nikudel 2016; Dos Santos and Bicalho 2017). The interpretation of the test data consists in the number of hammer-blows to drive a conic probe every 0.10 m depth interval (N_{10}), giving an idea of the soil resistance, similar to the SPT N-value. It is also possible to verify the similarity between the dimensions of the DPL and the CPT cone tips (Bastos 2016; Almeida et al. 2024), allowing for a comparison of the test data. This argument is further strengthened by the quasi-continuous nature of the DPL and the fact that it has no sampler, which has a greater influence on its behavior than its dynamic crimping mechanism (Lingwanda et al. 2015).

The DPL test interpretation can also be interpretated in terms of energy, resulting in a process known as rational interpretation (Lobo 2005; Odebrecht et al. 2005), allowing the determination of a unit tip resistance (q_p) and a unit friction resistance (τ_l). The energy-based interpretation of the DPL data enables a theoretical approach to the test for comparisons with CPT data. This paper presents the comparisons of q_p and τ_l with q_c and f_s in two well-documented unsaturated tropical soil sites in State of São Paulo, Brazil using the rational interpretation of the DPL data. The potentialities to use the rationally-interpretated DPL data in site characterization are presented and discussed.

2 IN SITU TESTING

2.1 *DPL*

Dynamic Probing Light (DPL) is a quasi-continuous penetration test, without collecting soil samples. The test is carried out in a similar way as the SPT, applying hammer-blows to advance a conical tip into the ground, resulting in a resistance index, N_{10}, which corresponds to the advance of 0.10 m of the probe. N_{10} gives an idea of the soil resistance, similar to the N-value of the SPT.

The test data are presented in terms of soil resistance and deformation parameters, as well as an estimate of the site profile, based on the changes observed in a penetration index.

The DPL is simple to operate and has advantages due to its compact configuration and accessibility, allowing continuous recording in areas that are difficult to access (Cunha & Nilsson 2003; Duarte et al. 2004; Bastos 2016, Dos Santos and Bicalho 2017; Arabpour Roghabadi et al. 2021; Almeida et al. 2024; Kotini et al. 2025).

The current standard for the DPL test is EN ISO 22476-2:2005 (2011), with components, dimensions and test procedures, having no restrictions regarding the test depth. Borowczyk and Frankopwski (1981) used the concept of critical depth, i.e. the point at which the influence of friction between the soil and the guide rods starts to compromise the data accuracy, an effect that can be ignored up to a depth of 10 m (Sanglerat 1972).

Recently, authors have been incorporating energy concepts into the interpretation of the test (Lobo 2005; Odebrecht et al. 2005; Ibañéz et al. 2012; Bastos 2016; Almeida et al. 2024;

Herrera et al. 2024, 2025). The energy-based interpretation of the DPL data allows for a better comparison with CPT data.

The DPL used was the DPL-T_SM-v1.2.0 model (Figure 1), manufactured by SOLOMAP, following the specifications of EN ISO 22476-2:2005+A1:2011, with manual lifting and driving of the hammer. The average efficiency of the hammer used, which is important for the rational interpretation of the test, was 70%.

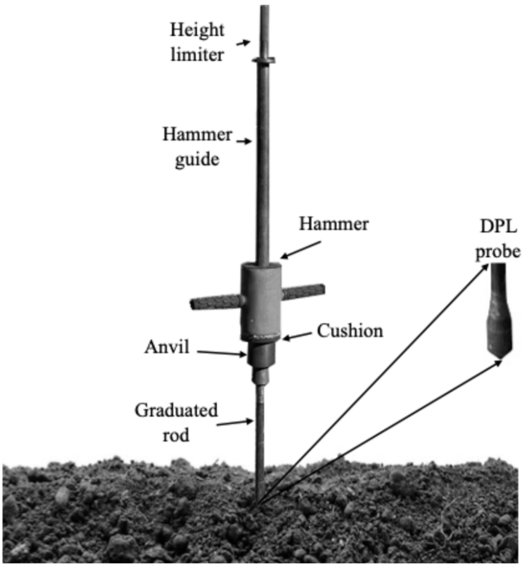


Figure 1 – DPL used.

2.2 *Rational Interpretation*

Rational interpretation is a way of standardizing analyses based on theoretical concepts, such as the energy that is transferred to the soil, through physical concepts of mechanical wave propagation and the work done by the penetrometer. Studies related to energy measurement in dynamic penetration tests have been carried out since the 1970s (Odebrecht et al. 2005).

The rational interpretation was developed by authors such as Odebrecht et al. (2005) and Lobo (2005). It consists of using the hammer efficiency values to calculate the energy transferred to the probe, as described by Lobo (2005), to obtain the unit tip resistance (q_p) and the unit friction resistance (τ_l).

The method proposed by Lobo (2005) was developed for calculating the load bearing capacity of piles using the average dynamic force obtained through the rational interpretation of the SPT, and authors such as Almeida et al. (2024) demonstrated that it can be extrapolated to other dynamic penetration tests such as the DPL. It considers the efficiency of the system and the hammer, geometric parameters of the rods, and the mass of the rods and the hammer. The calculation is detailed in Odebrecht et al. (2005), Lobo (2005) and Almeida et al. (2024), and is summarized below.

$$E_{probe} = \eta_3 . [E_r . (h + e) . M . g + e . M' . g] \tag{1}$$

$$E_{tip} = E_{probe} - E_f \tag{2}$$

$$e = 0.1/N_{10} \tag{3}$$

$$F_d = E_{probe}/e \tag{4}$$

$$F_d = F_{d.p} + F_{d,l} \tag{5}$$

$$q_p = F_{d,p}/a_p = 0.7\ F_d/a_p \tag{6}$$

$$\tau_l = F_{d,l}/a_l = 0.2\ F_d/a_l \tag{7}$$

where: E_{probe} is the energy delivered to the probe (J); η_3 the system efficiency; E_r the hammer efficiency; h the hammer drop height (m); e the penetrometer advance per blow (m); M the hammer mass (kg); g the acceleration due to gravity (m/s^2); M' the penetrometer mass (kg); E_{tip} the energy delivered to the tip (J); E_f the energy consumed by friction (J); F_d the average dynamic force (N); $F_{d,p}$ the dynamic tip force (N); $F_{d,l}$ the lateral dynamic force (N); a_p the area of the base of the tip (m^2); a_l the lateral area of the tip (m^2); q_p the unit tip resistance (N/m^2); τ_l the unit sleeve resistance (N/m^2).

3 EXPERIMENTAL RESEARCH SITES

3.1 *Unesp Site*

The soil profile at the Unesp research site consist of a red clayey fine sand. De Mio and Giacheti (2007) states that this site includes a colluvial Neo-Cenozoic deposit up to 13 m in depth, followed by a residual soil formed during the Quaternary. The MCT (Miniature, Compacted, Tropical) Classification System proposed by Nogami and Villibor (1981) for tropical soils was used to define and classify the soil with regards to its lateritic behavior, and classified the top 13 m as lateritic soil behavior (LA') followed by a non-lateritic soil behavior (NA').

This soil profile has undergone pedogenic and morphogenetic processes, that typically take place in tropical zones, resulting in partly saturated high- permeability soils (10^5 to 10^6 m/s) with cohesive-frictional and collapsible behavior (Dos Santos et al. 2019; Fernandes et al. 2022; Rocha et al. 2024). The groundwater table is not found up to 20 m depth at the site.

Figure 2 shows the grain size distribution, dry unit weight (γ_d), void ratio (*e*), and Atterberg limits (w_L and w_P) up to 9.0 m depth. The particle unit weight (γ_s) can be considered constant along depth, and the value is presented in the figure.

Four DPLs up to 7.0 m depth and four CPTs up to 8.0 m depth were conducted in this site in a dry season, and in a short period of time to eliminate the effect of seasonal influence on tests data (Réthági 1988).

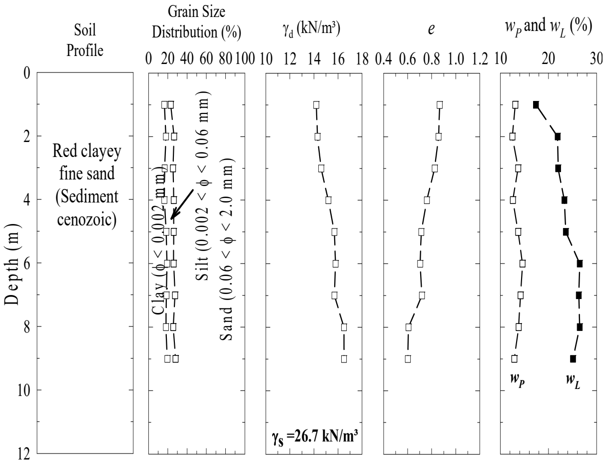


Figure 2– Soil profile and index properties of the Unesp site.

3.2 *USP Site*

The soil profile at the USP research site can be divided into a brown clayey fine sand, Cenozoic Sediment with lateritic behavior (LA'), up to about 6 m depth and exhibits collapsible behavior upon wetting (Machado & Vilar 1998). A Pebbles layer of about 0.5 m thick are found under this layer. The last layer is a residual soil from Sandstone, classified as a red clayey fine sand with non- lateritic behavior (NA').

Both layers are classified as clayey sand (SC) according to the Unified Soil Classification System (USCS). The groundwater table varies seasonally between 9 and 12 m below the ground surface (Silva et al. 2019; Morais et al. 2020; Rocha et al. 2021).

Figure 3 shows the soil profile obtained from SPT tests, along with index properties such as grain size distribution, dry unit weight (γ_d), void ratio (*e*), and Atterberg limits (w_L and w_P) for the studied site up to a depth of 12 m. The particle unit weight (γ_s) can be considered constant along depth, and the value is presented in the figure.

Three DPLs and three CPTs up to 8.0 m depth were conducted in this site. The tests were carried out in different periods, but all in a dry condition, allowing the comparison between the data.

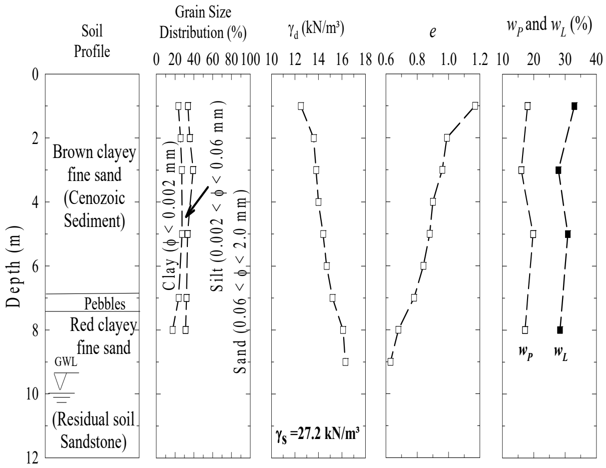


Figure 3 – Soil profile and index properties of the USP site.

4 DATA INTERPRETATION

DPL data was interpretated using the energy-based method proposed by Lobo (2005) and Odebrecht et al. (2005). Unit tip (q_p) and friction (τ_l) resistance profiles for the DPL are presented and compared to CPT data for the study sites. DPLs were performed as described previously, by applying hammer-blows and advancing the conical tip, counting the blows to advance 0.10 m, corresponding to the N_{10} value.

The variation profiles of N_{10}, q_c, and f_s data considered with depth are presented for the Unesp site (Figure 4) and for the Usp Site (Figure 5).

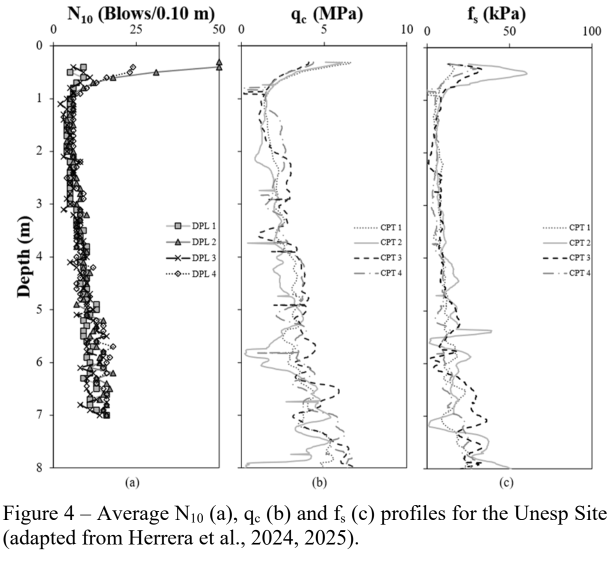


Figure 4 – Average N_{10} (a), q_c (b) and f_s (c) profiles for the Unesp Site (adapted from Herrera et al., 2024, 2025).

The four DPL (Figure 4a) and four CPT (Figure 4b-c) in the Unesp site are part of the data presented in Herrera et al. (2024, 2025). The tests were performed up to 7.0 and 8.0 m depth respectively and were conducted in a dry season.

For the USP site, the three DPLs (Figure 5a) were performed by Almeida et al. (2024) and three CPTs (Figure 5b-c) by Rocha (2018). The tests were performed up to 8.0 m depth. The tests were all conducted in a dry condition, allowing the comparison between the data without influence of the seasonal variation.

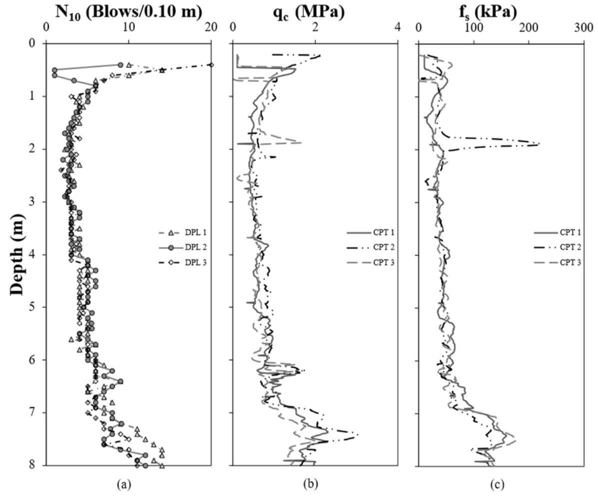


Figure 5 – Average N_{10} (a), q_c (b) and f_s (c) profiles for the Unesp Site (adapted from Rocha, 2018 and Almeida et al., 2024).

4.1 *Tip Resistance*

Bastos (2016), Almeida et al. (2024) and Herrera et al. (2024, 2025) discussed the unit tip resistance values obtained from the rational interpretation of the DPL test, which provided values similar to those of the cone resistance obtained with the CPT. A 100 kN CPT probe with 10 cm² cross sectional area was used to measure the tip resistance (q_c) and sleeve friction (f_s). A self-anchoring, multi-purpose push platform with a hydraulic system of 200 kN capacity was used for pushing the probe.

Four DPLs and four CPTs performed at the Unesp site in July/2024 were compared (Figure 4). Figure 6a present mean q_c and q_p profiles for the site, noticing that for the first meter depth there was a greater variability, that can be due to the presence of roots and coarse materials that can influence resistance. Figure 6b shows the relative error between q_c and q_p values. The average error considering the first meter depth values is 16.05%, in accordance with values obtained by Almeida et al. (2024) and Herrera et al. (2024, 2025). Disregarding the first meter depth, the average error is 9.83%.

Three DPLs performed at the USP site in June/2023 and three CPTs performed in April/2017 were compared. Figure 7a present mean q_c and q_p profiles for the site. Figure 7b shows the relative error between q_c and q_p values. The average error value is 15.99%, and it is in accordance with values obtained by Almeida et al. (2024) and Herrera et al. (2024, 2025).

4.2 *Friction Resistance*

Lobo (2005) compared shaft resistance values of instrumented piles data with unit sleeve resistance rationally interpreted from SPT data, noticing a scale effect in the transposition of the sleeve resistance mobilized by the SPT sampler to the pile, and the ratio between the sleeve resistances was around 0.20. A similar analysis was performed for the DPL and CPT data by Herrera et al. (2025).

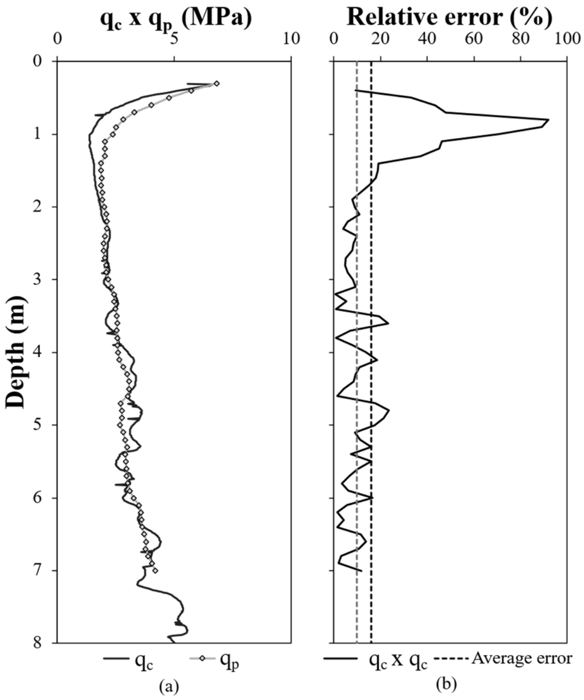


Figure 6 – Average q_c and q_p profiles (a) and relative error (b) for the Unesp Site.

The DPL sleeve resistances were compared to CPT sleeve friction, noticing the scale effect in the ratio between the rationally interpreted parameter (τ_l) and the measured one (f_s). A correction factor C_{DPL} was adopted to overcome the scale effect (Equation 8). This factor can be affected by the difference between the CPT and DPL friction sleeve dimensions, and also the soil's behavior.

$$C_{DPL} = \tau_l / f_s \tag{8}$$

For the Unesp site, τ_l values from DPL data were 15 to 20 times higher than the f_s obtained by the CPT. A value of 17.5 was considered representative for the study site. Four DPLs and four CPTs performed in July/2024 were compared. Figure 8a presents the average f_s and τ_l, considering the correction factor, profiles. It is possible to notice that the profiles were analogous after adopting the empirical factor, and the average error (Figure 8b) was equal to 14.02%.

For the USP site, f_s values are greater than those observed in the Unesp site. The correction factor was affected by the site's behavior and varied from 2.0 to 10.0. A value of 4.0 was considered representative for the study site. Three DPLs performed in June/2023 and three CPTs performed in April/2017 were compared. Figure 9a presents the average f_s and τ_l profiles, noticing that the profiles were analogous after adopting the empirical factor, and the average error (Figure 9b) was equal to 17.41%. These higher values for the USP site are associated with a greater variability after 6-meter depth for the DPL data.

4.3 *Soil Classification*

Considering that both q_p and τ_l values are analogous to the CPT data, it was possible to use these values in Robertson (2009) chart to identify soil behavior type based on DPL data.

The Robertson (2009) chart is based on normalized CPT data for overburden stress for very shallow and/or very deep CPT soundings. Herrera et al. (2025) proposed that the Normalized Friction ratio, F_r, and Normalized cone resistance, Q_t, for the DPL data should be considered such as Equations 9 and 10, respectively.

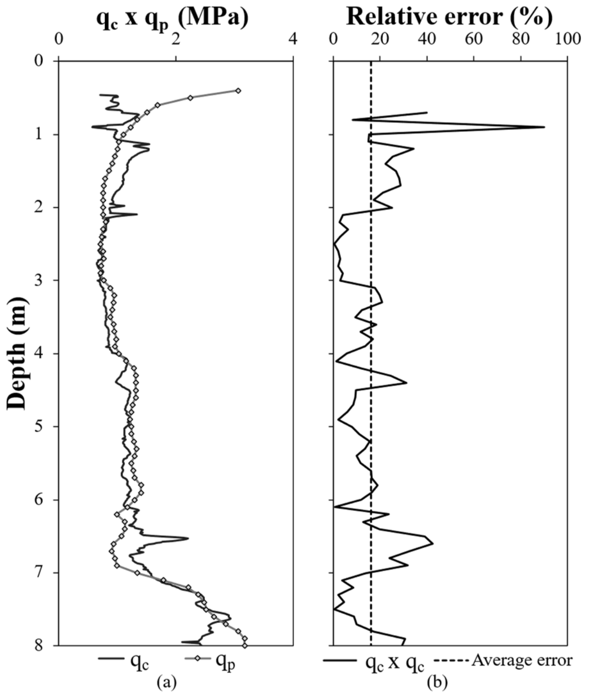


Figure 7 – Average q_c and q_p profiles (a) and relative error (b) for the USP Site.

$$F_{r,DPL} = \frac{\tau_l}{q_p - \sigma_{v0}} . 100\% \tag{9}$$

$$Q_{t,DPL} = (q_p - \sigma_{v0}) / \sigma'_{v0} \tag{10}$$

For the Unesp site, the soil was classified as a sandy silt to a sand for the CPT data, presenting a contractive-drained behavior at large strain (Figure 10a). The topsoil was classified as sand or dense sand, due to compaction, as well as the presence of roots and coarse materials. The site was classified as a sandy silt to sand based on the normalized DPL data, and the same behavior can be observed in the tail of the chart, for the topsoil. The classification using DPL and CPT data is in accordance with laboratory classification for this site.

For the USP site, the soil was classified as silt mixtures (clayey silt to silty clay) to clay (silty clay to clay), presenting dilative behavior at large strains and undrained behavior, for both CPT and DPL data (Figure 10b). This classification is in accordance with Rocha et al. (2024) and does not represent the soil type of this site profile. The soils from the USP site profile are characterized as clayey fine sand with contractive behavior in the drained triaxial (CD) tests and no dilation during failure (Machado 1998).

Rocha et al. (2024) discusses that two possible reasons to explain the difference between laboratory test condition and CPTu data interpretation are the unusual behavior of the USP site profile (bonding and cementation) and the intermediate permeability (10^{-5} to 10^{-8} m/s), typical for the soils of this site (Machado & Vilar 2003). The unusual behavior of unsaturated tropical soils cannot be correctly predicted by classical models for interpreting in situ tests and do not always apply to these soils (Rocha et al. 2024) and considerations are necessary for each site or for the geology (Robertson 2016).

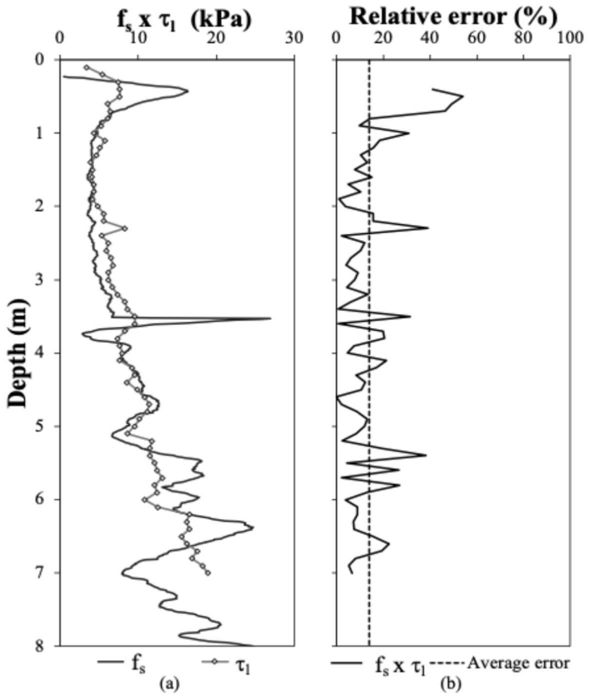


Figure 8 – Average f_s and τ_l (a) and relative error (b) for the Unesp Site considering a correction factor (C_{DPL}) of 17.5.

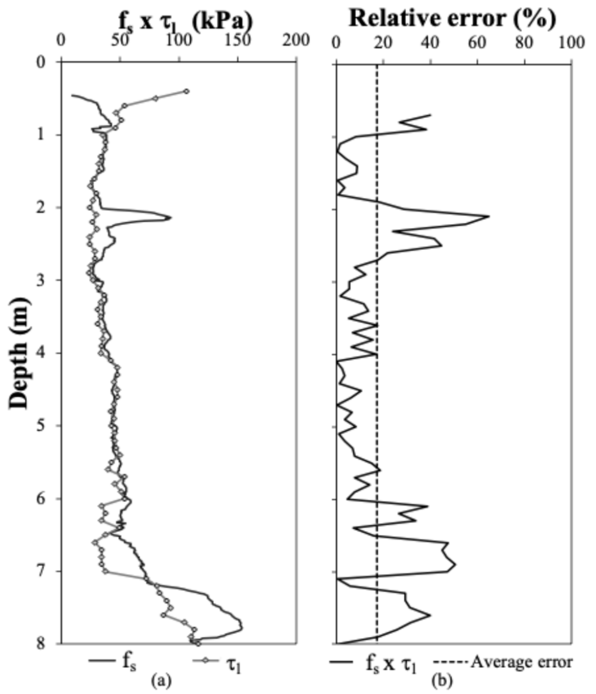
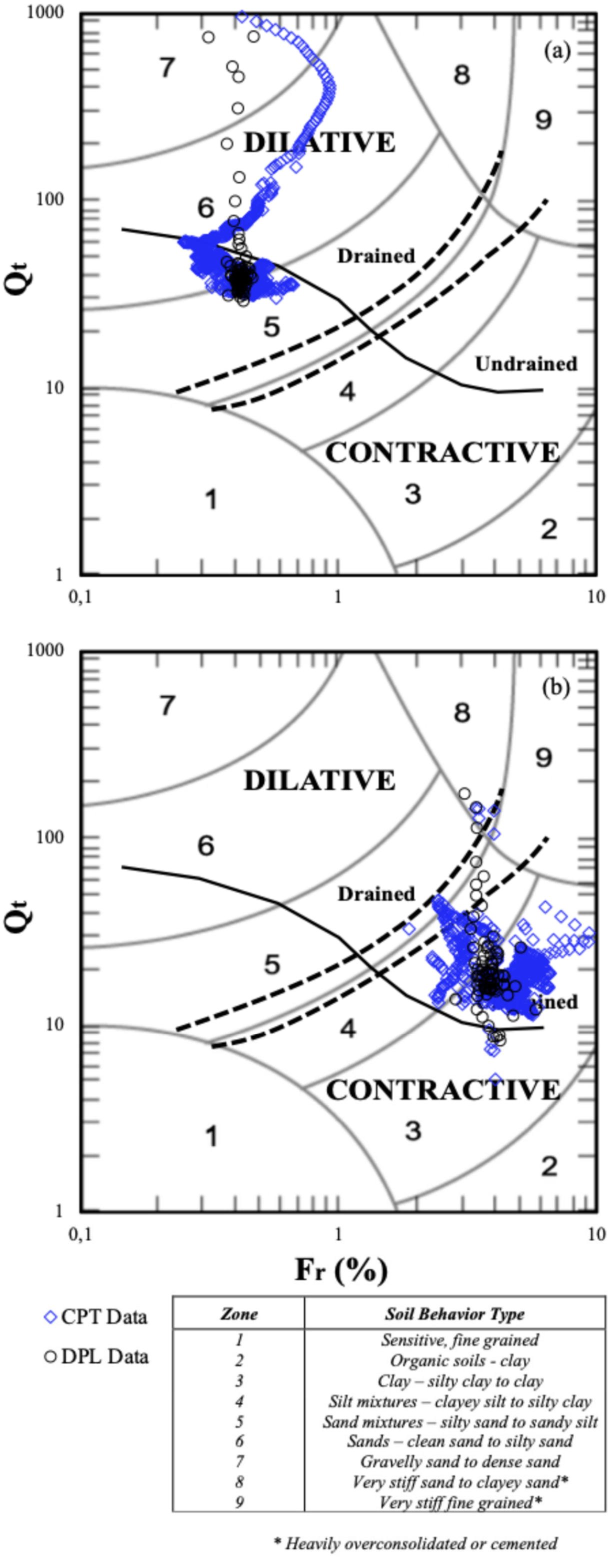


Figure 9 – Average f_s and τ_l (a) and relative error (b) for the USP Site considering a correction factor (C_{DPL}) of 4.0.

5 CONCLUSIONS

The DPL test is an interesting alternative for the preliminary characterization of tropical soil sites. DPL test data after the rational interpretation are analogous to CPT, especially when the scale effect on the unit frictional resistance is considered. Considering the energy-based interpretation, and empirical factors that can be adjusted for each site, DPL test data can be interpreted considering all the previous knowledge for soil classification by CPT. There was good accordance between the classification given by the CPT data and the DPL data for the study sites.



Zone	Soil Behavior Type
1	Sensitive, fine grained
2	Organic soils - clay
3	Clay – silty clay to clay
4	Silt mixtures – clayey silt to silty clay
5	Sand mixtures – silty sand to sandy silt
6	Sands – clean sand to silty sand
7	Gravelly sand to dense sand
8	Very stiff sand to clayey sand*
9	Very stiff fine grained*

* Heavily overconsolidated or cemented

Figure 10 – Soil classification for the (a) Unesp Site and the (b) USP Site.

6 ACKNOWLEDGEMENTS

The authors thank the São Paulo Research Foundation – FAPESP (Grant number 2023/01882-9), the Coordination for the Improvement of Higher Education Personnel – CAPES, the São Paulo State University – Unesp and the University of São Paulo – USP for supporting their research.

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