


Integrating downhole seismic testing into dynamic probing light (DPL): first results

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Technical Note

Keywords

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In situ test
DPL
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Hybrid test

Abstract

Dynamic probing light (DPL) is available among a wide range of dynamic penetrometers. This equipment can be used in locations where conventional sounding equipment may have limited access. Here, the shear wave velocity (V_s) determination by the downhole seismic technique is incorporated to the DPL to develop a hybrid test, the seismic DPL test, for the preliminary characterization of tropical soils. The corresponding equipment, test procedure and data interpretation of the seismic DPL (S-DPL) test are presented and discussed. S-DPL test campaigns were carried out at two experimental research sites where crosshole seismic tests were conducted to provide reference V_s profiles. The V_s profiles determined with the S-DPL test are in accordance with those determined with the crosshole test for both sites. The proposed hybrid test (S-DPL) has the potential to serve applications in preliminary site characterization, particularly at sites including unsaturated tropical soil profiles.

1. Introduction

Dynamic probing light (DPL) is a dynamic penetrometer known for its simplicity, easy manufacturability and ease-of-use (Figueiredo et al., 2012). The main advantage of the DPL test is that it is a compact piece of equipment that can access sites where conventional sounding equipment may have some restrictions, such as steep slopes, flooded areas, swamps, dense forests, and areas where heavy vehicles cannot access (Cunha & Nilsson, 2004). The DPL test is predominantly used in preliminary site investigations (Duarte et al., 2004) to obtain correlations with other in situ tests (Dos Santos & Bicalho, 2017; Hashemi & Nikudel, 2016; Mohammadi et al., 2008), to define the site stratigraphy from the variation in the cone penetration resistance index (Butcher et al., 1996), foundations, road design and slope stability analysis (Cunha & Nilsson, 2004).

The interpretation of the DPL test is generally based on the number of hammer-blows to drive the probe every 0.10 m (N_{10}) depth interval, which gives an idea of the soil resistance, similar to the N_{SPT} determined by the standard penetration test (SPT). It is important to know the energy transmitted to the system and the real energy delivered to the probe. This approach is known to be rational and has been used in the interpretation of the SPT. The unit tip resistance (q_p) can be determined by knowing the energy transmitted to the probe, which is responsible for the penetration of the DPL tip. It is therefore possible to apply these values to

shallow and deep foundation designs. Bastos (2016) and Almeida (2023) demonstrated that the q_p profile has the same trend and order of magnitude as the cone tip resistance profiles (q_c) obtained from cone penetration tests (CPTs) on an unsaturated tropical soil site.

The shear wave velocity (V_s) is an input parameter in soil dynamic and static analyses. Moreover, V_s can be used in soil classification, state parameter estimation, microstructure identification and collapsible soil identification (Robertson, 2016; Rocha et al., 2022, 2023; Schnaid et al., 2020). It would therefore be valuable to combine the potential of DPL test with the determination of V_s to serve applications in geotechnical design. In this way, this paper presents and describes a system and technique for performing and interpreting seismic DPL (S-DPL) test. The feasibility of combining the DPL test with the downhole seismic technique was evaluated at two experimental research sites where crosshole test data are available.

2. Background

2.1 Dynamic Probing Light (DPL)

Penetrometers are sounding devices that are used to estimate the resistance of soils and soft rocks by measuring the dynamic cone penetration resistance index (Hashemi & Nikudel, 2016; Mohammadi et al., 2008).

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The DPL test involves quasi continuous penetration, does not collect soil samples and the objective is to estimate the resistance and deformability parameters of the tested site as well as to define the soil profile from the variation in the penetration resistance index. The current standard that contains the components, dimensions and test procedures of the DPL test is EN ISO 22476-2:2005 (ISO, 2011). The number of blows that penetrated 0.1 m into the depth interval is registered during the test and is denoted as N_{10} .

The EN ISO 22476-2:2005 (ISO, 2011) standard does not restrict the test depth. Borowczyk & Frankowski (1981) used the concept of critical depth, the point at which the influence of friction between the soil and the guide rods starts to compromise the accuracy of the data. Sanglerat (1972) noted that the friction between the soil and the guide rods is low compared to the resistance of the soil and, in most cases, can be ignored up to a depth of 10 m.

Studies have been conducted with dynamic penetrometers all over the world in the last 50 years, most of which have sought empirical correlations with SPT and CPT (Dos Santos & Bicalho, 2017). Researchers have also attempted to correlate DPL test data with the soil shear strength, California Bearing Ratio (CBR) and degree of compaction (Butcher et al., 1996). Recent advances in DPL data interpretation have involved the use of dynamic instrumentation to determine hammer efficiency (ISO, 2011) and rational interpretation of the test.

The rational interpretation of the test consists of using the hammer efficiency values to calculate the energy transferred to the probe, as described by Odebrecht et al. (2005) and Ibáñez et al. (2012), to obtain the unit tip resistance (q_p) and the unit friction resistance (τ), as described by Lobo (2005).

Lobo (2005) proposed a method for calculating the load bearing capacity of piles using the average dynamic force obtained through the rational interpretation of the SPT, which can be extrapolated to other dynamic penetration tests. The method includes dividing the average dynamic force into two parts, one representing the contribution of the lateral dynamic force mobilized by the sampler or the probe and the other representing the dynamic force of the tip of the sampler or the probe, where:

$$F_d = F_{d,l} + F_{d,p} \quad (1)$$

where F_d is the average dynamic force, $F_{d,l}$ is the lateral dynamic force, and $F_{d,p}$ is the dynamic tip force.

The average dynamic force is calculated by Equation 2:

$$F_d = \frac{E_{probe}}{e} \quad (2)$$

where E_{probe} is the energy delivered to the sampler or the probe and e is the penetrometer advance per blow. The E_{probe} can be theoretically obtained or measured using instrumentation (Lobo, 2005; Odebrecht et al., 2005).

Using average estimated parameters, theoretical formulations of load capacity and spherical cavity expansion, Lobo (2005) observed that approximately 70% of F_d comes from the mobilization of tip resistance ($F_{d,p}$) and that the unit tip resistance (q_p) can be calculated by Equation 3:

$$q_p = \frac{F_{d,p}}{a_p} = \frac{0.7 \times F_d}{a_p} \quad (3)$$

The unit tip resistance (q_p) values obtained with the rational interpretation of the DPL test are analogous to the cone resistance values obtained with the CPT, as shown by Bastos (2016) and Almeida (2023).

2.2 The downhole test

A downhole test can be conducted to obtain the S-wave and P-wave velocities in the soil strata by using the theory of elasticity and assuming that the soil is an elastic, homogeneous and isotropic material.

The downhole seismic test measures the time it takes for a wave to propagate from the ground surface to the depth where the seismic transducer is located. The crosshole seismic test measures the time for a wave to propagate from a borehole to two seismic transducers located in two other boreholes at the same depth as the seismic source (ASTM, 2007). The crosshole seismic test is used as a reference for V_s values considering the horizontal path of the seismic wave.

The main devices used to perform a downhole seismic test are as follows (Butcher et al., 2005):

- Seismic transducer: a geophone or an accelerometer used to indicate the moment the seismic wave reaches the probe. Only accelerometers can be used in dynamic tests because geophones cannot withstand hammer impacts without being damaged;
- Seismic source: a device that generates the seismic wave; a shear beam and a hammer;
- Trigger: a system capable of identifying the time when the hammer hits the seismic source. It can be an electric, or an acceleration, force or impact transducer attached to the seismic font;
- The data acquisition system includes measurement devices, sensors, a computer, and data acquisition software to trigger, capture the traces and generate the data files.

3. Materials and methods

3.1 Research sites

Site investigation campaigns were conducted at two well-documented research sites: USP – São Carlos and Unesp – Bauru. These sites were selected because crosshole test data were available to use as a reference.

3.1.1 The USP Site

The USP (University of São Paulo) research site is located in the city of São Carlos, São Paulo State, Brazil. The city of São Carlos lies on rocks from the São Bento Group, which consists of sandstones from the Botucatu Formation and basic migmatites from the Serra Geral Formation (De Mio, 2005; Machado, 1998). The site profile has a sandstone residual soil layer covered by an unsaturated lateritic clayey sand layer (colluvial soil). A layer (0.2 m to 0.5 m) of pebbles separates the upper layer from the residual soil. The groundwater level varies seasonally between 9 m and 12 m below the ground surface. Both layers are classified as clayey sand (SC) according to the Unified Soil Classification System (USCS). Several site characterization campaigns with SPT, CPT, DMT, downhole, crosshole and laboratory tests were conducted at the site (Machado, 1998; Rocha, 2018; Rocha et al., 2021).

3.1.2 The Unesp Site

The Unesp (São Paulo State University) research site is in the city of Bauru, São Paulo state, Brazil. The city of Bauru is located in Paraná Sedimentary Basin. Sedimentary rocks from the Bauru Group (Marília and Adamantina Formations) cover the volcanic rocks (basalts) of the Serra Geral Formation that crop out toward the Tietê River valley (De Mio, 2005). The site profile has red clayey fine to medium sand with high porosity, and the relative density increases with depth. The upper layer (up to a depth of approximately 13.0 m) is a colluvial Neo-Cenozoic deposit with lateritic behavior (LA') over residual sandstone soil. The groundwater level was not found up to 30 m depth. These soils are classified as SM-SC by the Unified Soil Classification System (USCS) and have undergone pedogenic and morphogenetic processes typical of tropical zones. Several in situ (CPT, SPT, DMT, downhole and crosshole) and laboratory tests were conducted to characterize the site and determine the physical and mechanical properties of the soils (Giacheti et al., 2019; Rocha & Giacheti, 2018).

3.2 Crosshole tests

Two crosshole tests (CH1 and CH2) were previously performed up to approximately 9 m depth at the USP site (Giacheti et al., 2003; Giacheti, 1991), and one crosshole test (CH1) was performed up to approximately 14 m depth at the Unesp site (Giacheti, 1991) following the ASTM D4428-07 (ASTM, 2007). Three boreholes 150 mm in diameter and spaced 3 m apart were installed for each test. The two receiver boreholes were cased with PVC pipes 75 mm in diameter, and the source borehole with PVC pipes 85 mm in diameter. A grout mix that closely matched the soil density was used. The data were taken at every 1 m depth interval for test CH1, every 0.5 m depth interval for test CH2 at the

USP site, and every 0.5 m depth interval at the Unesp site. The test procedure consisted of generating reverse polarity shear waves, first by impacting one end of a hammer source and then by impacting the other end. Volts *versus* time traces, corresponding to each impact, were registered on an oscilloscope and recorded in a notebook for subsequent processing and analysis.

3.3 DPL

3.3.1 Equipment

The DPL model DPL-T_SM-v1.2.0 was used, and this device was made by SOLOMAP following the EN ISO 22476-2:2005 (ISO, 2011) specifications (Figure 1). The hammer is raised and released manually, and it has a wood cushion between the hammer and the anvil.

3.3.2 Seismic DPL probe

A conical probe with a slot to insert the sensor was manufactured and named the seismic DPL probe (Figure 2). A seismic transducer was incorporated into this probe to determine the shear-wave velocity.



Figure 1. The DPL equipment used in this study.

The seismic transducer was a high-sensitivity ICP accelerometer from PCB Piezotronics, Model 333B32. This device has a 100 mV/g sensitivity, ± 50 g measurement range and a frequency range from 0.5 Hz to 3000.0 Hz (PCB PIEZOTRONICS, 2002). The cable is also from PCB Piezotronics, the 003C model.

The seismic source has a shear beam made with a piece of wood reinforced with steel and has steel blades on its base to prevent it from sliding during blows applied by a small sledgehammer.

Two different triggers were tested to start recording the seismic traces by the data acquisition system immediately after the sledgehammer hit the seismic source: a) an impact sensor from Murata Electronics, model PKS1-4A10, with a 40 mV/g sensitivity attached to the seismic source, and b) an electrical circuit that closes and the electrical signal triggers the data acquisition system. The electrical trigger is simple and reliable to use, as discussed by Campanella & Stewart (1992), and it was selected for use.

The accelerometer and the trigger traces (when the impact sensor was used) were captured using a signal amplifier model MX410 from HBM. The amplifier has four data acquisition channels, an individual sample rate of up to 100000 samples/second, and a 40 kHz bandwidth and is compatible with ICP sensors (HBM, 2020). HBM MX410 can be ground to prevent signal disturbances due to electromagnetic interference (HBM, 2020).

CatmanEasy AP software version 3.5 was used with the HBM MX410 to visualize and interpret the data because it has a data acquisition module and a data visualization module for the data collected from the sensors connected to the signal amplifier.

3.3.3 The S-DPL test procedure

The DPL test is conducted as described by EN ISO 22476-2:2005 (ISO, 2011) to the depth at which the downhole seismic test is to be conducted. The data acquisition software module is turned on after the system is appropriately grounded. The sledgehammer is then struck on the right side of the seismic source. After three blows to one side of the seismic source, another three blows are delivered to the other side of the seismic source. The arrival time of the seismic wave is the average time interval determined for the two directions. When the shear beam is struck in opposite directions, it produces shear waves of opposite polarity (Butcher et al., 2005) making it easier to identify the time of arrival of the wave. The traces of the two polarized waves are shown in Figure 3.

The S-DPL test is resumed until the next depth at which the V_s will be determined, after completing the acquisition of the time-of-arrival data the test is resumed and so on to the desired depth. The S-DPL test arrangement is shown in Figure 4, all the tests were conducted up to 8 m depth, with seismic waves generated every 0.5 m depth interval.

The shear wave velocity is determined by the pseudo interval method (Butcher et al., 2005) because the seismic DPL probe has only one sensor. The seismic test data were exported, and an anti-aliasing filter was used during data acquisition, as reported by Butcher et al. (2005). The data were analyzed by using commercial SPAS software to analyze the seismic traces and to calculate the shear wave velocity using the cross-correlation method (Butcher et al., 2005). All the waves in each test were initially adjusted to a total length of 400 ms. Waves with poor quality recordings or with any identified problem in a visual assessment were excluded. This exclusion process also ensured that the waves were correctly polarized for the strokes on opposite sides of the source. A Butterworth filter was then applied. The bandpass filter cutoffs were set at 40 Hz to 400 Hz, order 3, for the test conducted at the USP

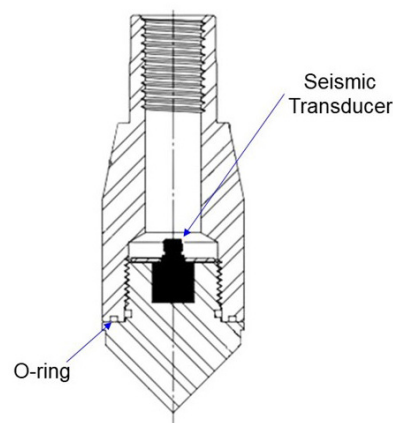


Figure 2. Schematic representation of the seismic DPL probe.

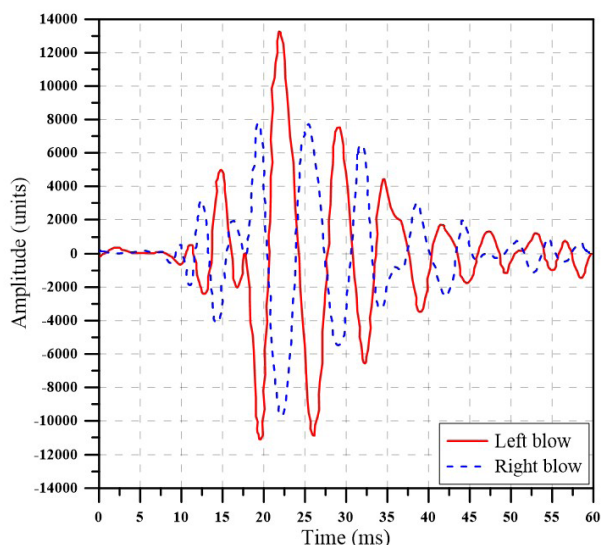


Figure 3. Traces of two polarized waves generated during one seismic test at the same depth at the Unesp site.

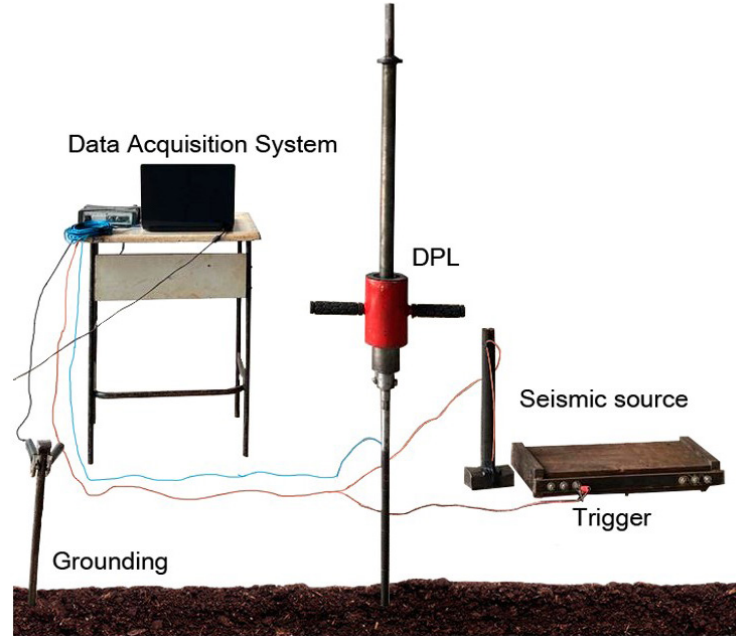


Figure 4. The S-DPL test arrangement.

site. The recordings of the tests conducted at the Unesp site are noisier, so in this case, a bandpass filter of 50 Hz to 300 Hz, order 4, was used. A typical V_s profile obtained with the SPAS software as previously described is shown in Figure 5.

4. Test data and analysis

4.1 The USP site

Three S-DPL tests were conducted at the USP site in July 2023, near one of the two crosshole tests conducted by Giacheti (1991) and by Giacheti et al. (2003). The unit tip resistance (q_p) profiles obtained with the DPL test using rational interpretation and the shear wave velocity (V_s) profiles obtained with the S-DPL test are presented together with the two crosshole V_s profiles in Figure 6.

The q_p profiles are quite repeatable, and the V_s profiles determined with the S-DPL are in accordance with the V_s profiles determined with crosshole tests by Giacheti (1991) and Giacheti et al. (2003). The shear wave velocities have an average relative error difference of 9.8% when compared with Giacheti (1991) data and 11.9% when compared with Giacheti et al. (2003) data. The relative error was calculated from Equation 4 (ISO, 1994).

$$\delta_y = \left(\frac{\Delta y}{y} \right) \cdot 100 = \left(\frac{y_i - y}{y} \right) \cdot 100 \quad (4)$$

where δ_y is the relative error; Δy is the absolute error; y is the true value of V_s (the assumed reference values from the crosshole test); and y_i is the measured value of V_s from the S-DPL.

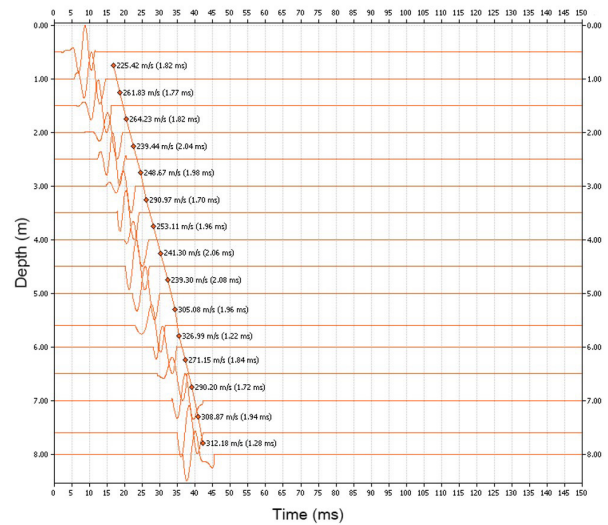


Figure 5. Typical seismic traces after applying the filters using the SPAS software for one downhole test conducted at the USP site to determine the V_s profile. The V_s values and the time intervals for each depth are also presented.

4.2 The Unesp site

Three S-DPL tests were conducted at the Unesp site, in July and in September 2023, near the crosshole test conducted by Giacheti et al. (2003). The unit tip resistance (q_p) profiles obtained with the DPL test using rational interpretation and the V_s profiles obtained with the S-DPL test are presented together with the crosshole V_s profile in Figure 7.

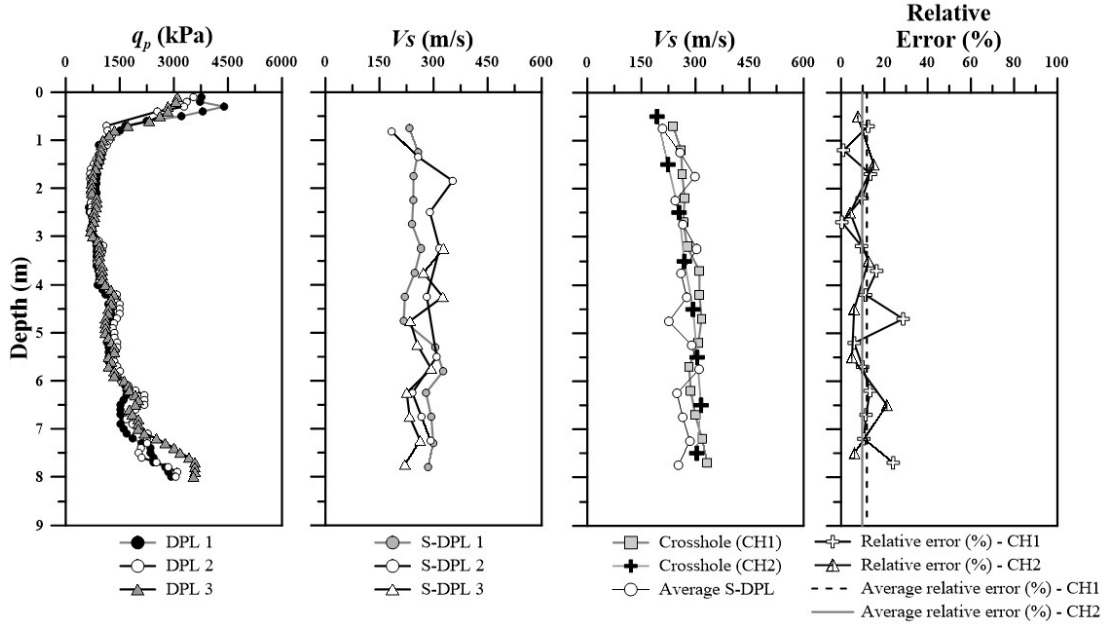


Figure 6. q_p and V_s profiles from the S-DPL tests together with crosshole seismic data collected at the USP site.

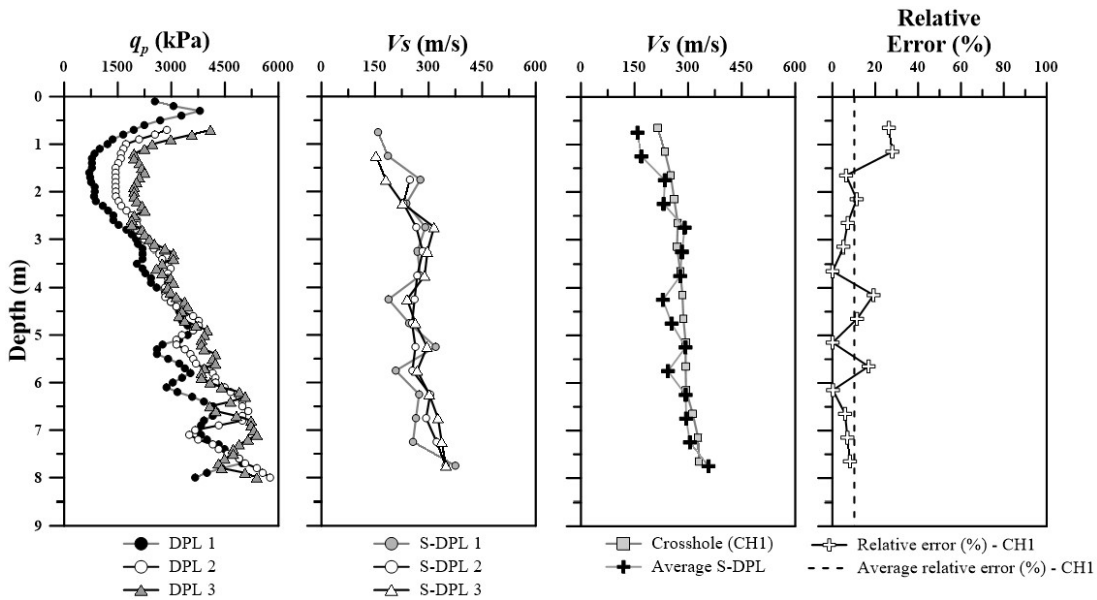


Figure 7. q_p and V_s profiles from the S-DPL tests together with crosshole seismic data collected at the Unesp site.

The q_p profiles are more variable than those observed at the USP site, and the V_s profiles determined with the S-DPL are in accordance with the V_s profile determined with the crosshole test by Giacheti et al. (2003), with an average relative difference of 9.1%, similar to what was found at the USP site.

5. Conclusions

A system to conduct the seismic DPL test and a method to interpret the seismic test data are presented and discussed. The V_s profiles determined with the seismic DPL have an average relative difference equal to 9.8% for one crosshole

test and 11.9% for the other crosshole test at the USP site. An average relative difference of 9.1% was found for one crosshole test conducted at the Unesp site. These findings indicate that the equipment, procedure, and data interpretation of the seismic downhole test conducted together with the DPL test have the potential to be used as preliminary tests in the site characterization of soils.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Caio Henrique de Castro Almeida: conceptualization, data curation, formal analysis, writing – original draft, writing – review & editing. Heraldo Luiz Giacheti: conceptualization, methodology, supervision, funding acquisition, writing – original draft, writing – review & editing. Breno Padovezi Rocha: conceptualization, data curation, formal analysis, methodology, writing – original draft, writing – review & editing. Edmundo Rogério Esquivel: supervision, validation, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols and abbreviations

e	Penetrometer advance per blow
q_c	Cone tip resistance
q_p	Unit tip resistance
y	True value
y_i	Measured value
CPT	Cone Penetration Tests
DMT	Dilatometer Tests
DPL	Dynamic Probing Light
E_{probe}	Energy delivered to the sampler or the probe
F_d	Average dynamic force
$F_{d,l}$	Lateral dynamic force
F_d	Dynamic tip force
N_{10}	Number of blows to penetrate 0.1 m

N_{20}	Number of blows to penetrate 0.2 m
N_{SPT}	SPT N value
SPT	Standard Penetration Tests
S-DPL	Seismic DPL
SC	Clayey sand
SM	Silty sand
USCS	Unified System Classification Soils
V_s	Shear wave velocity
τ	Unit friction resistance
δy	Relative error
Δy	Absolute error

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