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# DEVELOPMENT AND VALIDATION OF AN UPDATED SYSTEM FOR DOWN-HOLE SEISMIC TESTING TOGETHER WITH PIEZOCONE

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**ABSTRACT.** This paper presents the updated version of a system that uses a probe and software to carry out down-hole seismic testing in conjunction with piezocone to determine shear wave ($V_s$) and compressional wave ($V_P$) velocities for geotechnical site characterization. The system was used in down-hole tests carried out at experimental research sites located in the interior of the state of São Paulo, Brazil, where reference $V_s$ and $V_P$ values determined by cross-hole and down-hole tests are available. The updated seismic probe has six geophones: three for *S* wave recordings spaced 0.5 m apart and three for *P* wave recordings, also spaced 0.5 m apart. The updated software integrates data acquisition, allows the visualization of *S* and *P* wave traces and calculates $V_s$ using the true interval method. The $V_P$ profiles could only be determined by the pseudo-time interval using commercial software. The developed system is considered efficient for determining $V_s$ profiles in the way it was used. Further studies are needed to better understand the propagation of *P* waves, as well as to improve the system and the method for determining $V_P$ profiles.

**Keywords:** geophysical site characterization; S waves; P waves; hybrid tests; seismic probe

## INTRODUCTION

Site investigation consists of defining the stratigraphic profile and estimating the geotechnical parameters required for each project. Hybrid tests are an interesting alternative to traditional tests to do it, as they allow one or more complementary data to be obtained to those normally obtained by in-situ tests such as standard penetration test (SPT), cone penetration test (CPT) and flat dilatometer test (DMT). Conventional penetration tests can be complemented by measuring the propagation velocity of compression (*P*) and shear *(S*) waves by using seismic tests. In this way, it is possible to calculate the propagation velocity of these waves ($V_P$ and $V_S$) and determine the maximum shear modulus ($G_0$), dynamic Young's modulus ($E_0$) and Poisson's ratio (ν), as well as to estimate the position of the groundwater level (Leong & Cheng, 2016; Rocha & Giacheti, 2019; Astuto et al., 2023).

The piezocone penetration test (CPTu) is part of another family of in-situ tests, their use of which has become increasingly widespread since the 1970s (Robertson, 2016). It consists of the quasi-static driving of a conical probe and the recording on a computer of the soil response to this driving, usually at 20 mm depth intervals, i.e. the cone resistance ($q_c$), sleeve friction ($f_s$) and pore pressure ($u$). After proper interpretation, these data make it possible to define site stratigraphy (De Mio & Giacheti, 2007) and estimate the design parameters based on correlations (Lunne et al., 2009). In the 1980s, a system for acquiring seismic waves was incorporated into the piezocone, and it became known as a seismic piezocone test (SCPTu). The propagation velocity of shear ($V_S$) and compression ($V_P$) waves can be determined by this system.

Several authors suggest using in-situ tests, such as seismic piezocone test (SCPTu) and seismic flat dilatometer test (SDMT) or laboratory tests, such as triaxial tests equipped with bender elements to assess the unusual soil behavior of sands and clays, the static and dynamic liquefaction potential of tailings, identify collapsible soils, as well as identify the position of the groundwater table based on the velocity of compression waves ($V_P$) (Schnaid & Yu, 2007; Jamiolkowski, 2012; Astuto et al., 2023; Rocha et al., 2022; 2023).

It is interesting to note that the *SCPTu* has the same characteristics as the piezocone test, with the addition of one or more seismic sensors inside. Vitali et al. (2012) point out that the main advantage of this type of test is its cost, which is lower than that of the traditional cross-hole (CH) test. Vitali et al. (2012) developed a seismic probe with three geophones spaced 0.5 m apart, making it possible to obtain three records for the same blow, increasing the interpretation possibilities. In this way, it is possible to determine the shear wave velocities for the same strike on a source located on the ground surface.

It is important to note that a modern, up-to-date system (hardware and software) will enable a better definition of the arrival time of seismic *S* and *P*-waves and thus the calculation of the dynamic elasticity parameters of the soil and the estimative of the position of the water level. This last piece of information is important, especially in unsaturated soil profiles and in tailings dams, where the knowledge of the water level position and its temporal variation is important for predicting the performance of these geomaterials (Jamiolkowski, 2012).

This paper presents the updated system, hardware and software, i.e. the seismic probe and the data acquisition and processing software, to determine *S* and *P*-wave propagation velocity profiles in conjunction with the piezocone to calculate the dynamic soil parameters. In addition, the aim is to assess the possibility of identifying the position of the groundwater level from the *P*-wave velocities and their interpretation over depth.

## THE UPDATED SYSTEM FOR DOWN-HOLE SEISMIC TESTS

The updated system has five parts:

a) A machined steel probe with six geophones;

b) A data acquisition system;

c) A software for data acquisition and interpretation;

d) An electrical trigger; and

e) A source to generate seismic waves.

The idea is to perform the *CPTu* using standard equipment and after that the down-hole seismic test is carried out pushing a probe in the same hole using the developed system. For this reason, the diameter of the probe is higher than a standard cone. Each of the components of the system and the laboratory



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development tests are presented and discussed, as well as the performance during the tests and the data interpretation.

**The seismic probe**

A machined steel seismic probe was built with three spots, spaced 0.5 m apart, each with two geophones, meaning that this probe has a total of six geophones inside, unlike the probe by Amoroso et al. (2016). The seismic probe has a length of 1.176 m and a diameter of 44.0 mm. The pair of geophones, spaced 0.5 m apart, make it possible to determine the values of wave propagation velocities using the true time interval method as well as the pseudo time interval. Figure 1 shows a photo of this updated seismic probe.

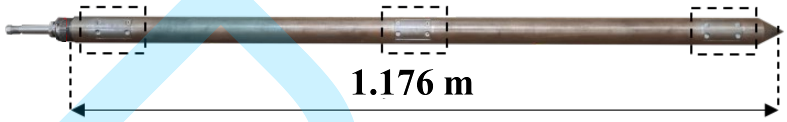


Figure 1: The seismic probe highlighting the three spots where the geophones were installed.

Six records can be registered at different depths for just one stroke, increasing the possibilities of testing interpretation with a more detailed $V_S$ and $V_P$ profile (every 0.5 m interval). It is essential to keep the axis of vibration of geophones parallel to the direction of the strike and maintain this position during the test. It is one of the most important factors to the success of the test (Vitali et al., 2012).

One O-ring was inserted in each of the spots where the geophones are installed to ensure that no water infiltrates into the probe. The waterproofness test was carried out by inserting the probe into a PVC tube filled with water. The pipe was closed, and a pressure actuator was used to apply 100 kPa, 200 kPa, 300 kPa and 350 kPa. Each of these pressures was applied for 120 minutes. No decrease in pressure or leakage of liquid inside the *PVC* pipe was observed for each of the pressures applied. The geophones covers were removed after the waterproofness test was concluded, and it was confirmed by visual observation that there was no water inside the probe.

***Geophones***

The used geophones were manufactured by Geospace, model OMNI GS-14. Three of them were installed parallel to the axis of the probe (GS-14-L3) and the other three, perpendicular to this axis (GS-14-L9). The main characteristics of these sensors are: natural frequency of 28 Hz, sensitivity of 35.4 V/m/s and spurious frequency of 400 Hz. It maintains the factory specifications for angles below 15 degrees to the axis of vibration. It is important to position the geophone axes correctly and to maintain this position throughout the test, as described by Vitali et al. (2012).

The inside of the probe was prepared so that the geophones were as stable as possible and did not move during the push. Figure 2 shows the geophones to be installed inside the probe. Thin sheets of Styrofoam are used between the geophones to prevent one geophone from contacting another.

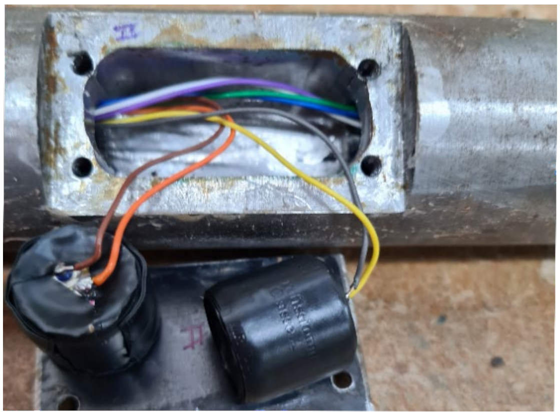

Figure 2: Geophones to be installed inside the probe.

An 18-way connector and a cable made up of 9 twisted pairs of wires (one positive and one negative pole per pair) were installed at the end opposite the probe tip. One of these pairs of wires was used for each geophone. A sealing ring has been used on this connector to allow the probe to be used underwater. The cable was grounded by connecting one end of a wire to the internal circuit of the cable and the other end to the AI GROUND analog channel of the data acquisition system.

***Data acquisition***

Initially, a 12-bit resolution, 16-channel analog-digital module was used for data acquisition. This equipment is the ADS 2000 model, with an AI-2161 signal conditioner, manufactured by Lynx Electronic Technology. The data acquisition software on the Visual Basic platform was developed by Pedrini et al. (2018). This system enables a maximum data acquisition frequency of 15 kHz, which is lower than the minimum value recommended by Butcher et al. (2005), which is 20 kHz. Although this data acquisition system performed well, it was replaced by a system from National Instruments, model NI USB-6251. This device also has 16 channels but has a sampling rate of 1.25 MHz per channel and a resolution of 16 bits. The software has been updated for data acquisition and interpretation on the Labview platform. The decision to upgrade this system was due to its high data acquisition capacity at a relatively low cost. This system makes it possible to view all the seismic waves arriving at the selected geophones after the blow has been applied and to check whether the waves have been greatly affected by external noise or whether the arrival time of the signals at the geophones is very different from each other. In this software, the users can enter the distances between the geophones and the depth of the sensor closest to the conical tip about the ground surface, and the horizontal distance between the axis of the seismic source. For each blow applied on the seismic source, a .txt file is generated and saved on the computer, so that the arrival times of three selected geophones (geophones installed in a horizontal or vertical position) are recorded in the same file. In addition, this software applies a 40 Hz Butterworth high-pass filter and a 400 Hz low-pass filter, both of order

3 recommended by Campanella & Stewart (1992) and Vitali et al. (2012). Two channels were used for each geophone to allow differential reading to enhance the recorded data quality from the sensor plus noise, while the other provides the inverted signal from the sensor plus noise. Thus, the recorded signal is the difference between the two signals, which corresponds to the duplicate signal of the noise-free sensor. This approach is interesting but not mandatory, as noise can be removed with digital filtering.

***Signal processing***

Butcher et al. (2005) recommend recording the signal without any modifications and then apply a digital filter that does not delay the signal to remove the noise.

The application of the third-order low-pass Butterworth digital filter with a cut-off frequency of 400 Hz, which corresponds to the spurious frequency of the geophones, completely removed the noise signal without distorting the main pulse of the *S* waves, which occurs between the frequencies of 40 and 120 Hz (Campanella & Stewart, 1992).

The software displays the original and filtered signals on the computer screen during the test run, allowing visual inspection of the signals prior to recording the data.

***Trigger***

The trigger device has the function of triggering the data acquisition system when the seismic event is generated. Campanella & Stewart (1992) compared several trigger devices and concluded that an electrical trigger is the simplest and most reliable device to be used.

The trigger used is a digital contact type coupled to a steel-headed hammer weighing around 2 kg, following the recommendations of Pedrini et al. (2018). This trigger consists of two intertwined wires, in which the first wire is connected to the hammer head and the PFI 0/PI.0 digital channel of the acquisition system, while the second wire is connected to the seismic source and the +5 V digital channel, resulting in an open electrical circuit. The electrical circuit closes when the hammer head hits the seismic source, and the seismic waves are recorded by the acquisition system. After the blow has been applied, the electrical circuit is opened again, allowing a new strike to be delivered.

***Pushing equipment***

A multi-purpose pushing equipment manufactured by Pagani Geotechnical was used to carry out the CPTu and the down-hole seismic tests. This equipment has a pushing capacity of 150 kN and it is anchored to the ground by two anchors. It is noteworthy that pushing the seismic probe into the ground ensures a perfect contact between the sensor and the soil, which is fundamental to ensure good quality of the recorded signals.

***The seismic source***

One of the sources used consists of a steel bar loaded against the ground by the pushing equipment, which

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is struck by a 2 kg sledgehammer. This type of source is appropriate for generating predominantly *S* waves and allows generating reversed polarity waves striking both sides of the steel bar.

This source can be positioned in the front or behind the pushing equipment. The rear leveling rod provides a higher vertical load than the front leveling rod ensuring better contact with the ground, however, on the rear side, the source will be 1.8 m apart from the hole. This horizontal distance will provide reliable $V_S$ data only after 4 to 5 m depth, as shown by Butcher & Powell (1995) and by Vitali et al. (2012). These authors recommend the use of a horizontal distance lower than 1 m between the seismic source and the hole. The horizontal distance is 0.3 m when the source is placed in front of the push equipment. In this case, two sources are used to make it easier to reverse the polarity of the waves. Figure 3 shows the seismic source positioned in the front side of the pushing equipment.

The *P* wave sources were located at 2.5 m from the rods. The source also needs to have good contact with the ground surface when generating *P* wave. So, grooves were used in the lower part of the source to improve its contact with the ground. In addition, at least 20 strokes were applied to the top of the source and a bit of wet sand was placed at the base of the source to improve its contact with the ground. Another way to improve contact between the seismic source and the ground is to use hooks driven into the ground with a hammer. Tests carried out in the field have shown that the combined methods (stroke, wet sand, and hooks) improve the contact between the seismic source and the ground (Figure 4).

Figure 3: The seismic source placed in the front side of the pushing equipment to generate predominantly *S* waves.

Figure 4: Seismic source generates predominantly *P* waves.

***Data interpretation***

The shear wave velocities ($V_S$) were calculated by the time interval method recommended by Butcher et al. (2005). The time interval ($\Delta T = T_2 - T_1$) is the difference between the first arrival time of seismic waves to the transducers at two distances ($\Delta S = S_2 - S_1$) of the source. The difference between the distances traveled by the *S* waves, assuming a linear pathway, divided by the time interval provides the shear wave velocity ($V_S$), given by the equation (1).

$$V_S = \frac{S_2 - S_1}{T_2 - T_1} \quad (1)$$

The data was interpreted using the cross-correlation method, selecting one complete revolution of the main *S* wave pulse, as recommended by Vitali et al. (2012). Details on the seismic test data interpretation are presented by these authors. According Campanella & Stewart (1992), "the cross-correlation of signals at adjacent depths is determined by shifting the lower signal, relative to the upper signal, in steps equal to the time interval between the digitized points of the signals. At each shift, the sum of the products of the signal amplitudes at each interval gives the cross-correlation for that shift. After shifting through all the time intervals, the cross-correlation can be plotted versus the time shift, and the time shift giving the greatest sum is taken as the time shift interval used to calculate the interval velocity". This method presents the advantage of using the entire recorded signal to calculate the time interval; however, software is necessary for data reduction and interpretation.

The true time interval is obtained recording the response of two sensors placed at two different depths considering the same seismic event. This method eliminates errors associated with inaccuracies in the trigger device, variations in the generated waves and inaccuracies in depth measurements. This technique requires the use of seismic transducers with identical responses. Figure 5 presents a schematic illustration of the true interval method.

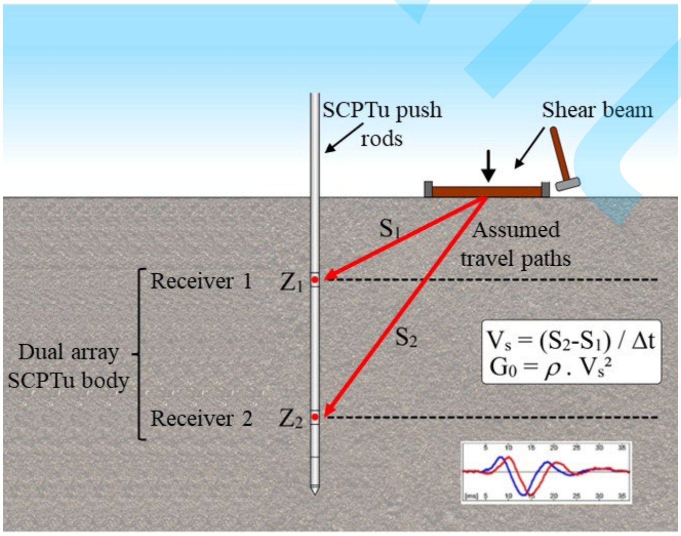


Figure 5: Schematic representation of SCPTu with two seismic sensors at different depths (adapted from Butcher et al., 2005).

Shear wave velocity values were calculated using a data acquisition software developed using the Labview platform. This software uses the cross-correlation method and filters the signals from the three seismic sensors. The $V_S$ values are calculated with the three possible combinations of true interval method and recorded in a text file (*.*txt*) throughout the test. So, the step of data interpretation is almost simultaneous to the test execution, giving plenty of speed and convenience to the test.

The moment of arrival of the *P* waves corresponds to the first deflection of the signal. In places where there is a lot of noise, this arrival can be masked, making it difficult to identify the first arrival of these waves. Seismic sources are usually rich in the production of *S*-waves, so signal stacking is used to determine the moment of arrival of the *P* waves. Thus, the strikes are repeated several times at the same depth to obtain a record that allows the moment of arrival of the *P* waves to be identified. Figure 6 illustrates the moment of arrival of the *P* and *S* waves in a typical cross-hole test trace.

The way the seismic probe was designed and built allows obtaining two $V_S$ values with the geophones spaced 0.5 m apart and one $V_S$ value with the geophones spaced 1m for every single seismic event. It was assumed that the results are equivalent and the use of smaller geophone spacing would be more appropriate because the waves would be more similar, facilitating the application of the cross-correlation method, and pathway followed by seismic waves ($L_1$ - $L_2$) would be closer to the spacing of the geophones, reducing errors associated with wave propagation path.

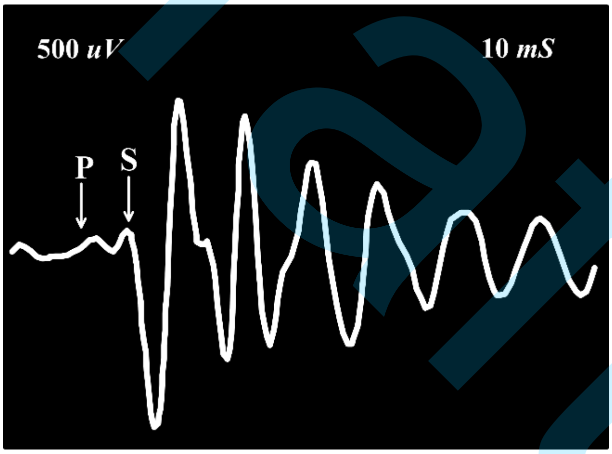


Figure 6: Typical cross-hole arrival trace (adapted from Dourado, 1984).

## VALIDATION

To validate the system, several tests were conducted at three sites located in the interior of São Paulo State, Brazil: University of São Paulo (USP) - São Carlos Campus, São Paulo State University (Unesp) - Bauru Campus and the Municipal Botanical Garden of Bauru. The USP - São Carlos and Unesp - Bauru sites were chosen because cross-hole and SDMT data are available (Giacheti et al., 2006a; Giacheti et al., 2006b; Rocha & Giacheti, 2018) and served as a reference for comparison with the proposed updated system. The Municipal Botanical Garden of Bauru site was chosen due to the presence of a groundwater table close to the ground surface.

Cross-hole seismic testing, which is carried out in boreholes is the geophysical technique that provides the most accurate velocity profile of seismic waves shear waves ($S$ waves) and compressional waves ($P$ waves) as a function of depth. In this sense, cross-hole test data were used as a "reference" for evaluating the accuracy of the $V_S$ and $V_P$ profiles obtained from seismic methods (e.g., seismic cone, seismic dilatometer, spectral analysis of surface waves (Anderson et al., 2007; Gandolfo, 2022; Fernandes et al., 2023).

The cross-hole from Unesp – Bauru and USP – São Carlos sites were carried out in three boreholes, one for the seismic source and the other two for the triaxial geophones. PVC casing was grouted in the borehole according to ASTM D4428 (2007).

An error analysis was performed to verify the accuracy of $V_P$ and $V_S$ values determined with the updated system. The relative error was used (equation 2) to assess the quality of the measurement process and the accuracy of the $V_S$ and $V_P$ values determined (ISO-5725-1, 1994).

$$E_r = \left(\frac{\Delta V}{V_t}\right).100 = \left(\frac{V_m - V_t}{V_t}\right).100 \quad (2)$$

where $E_r$: relative error; $\Delta V$: absolute error; $V_t$: true value of $V_S$ and $V_P$, the assumed reference values from cross-hole and SDMT; $V_m$: measured value of $V_S$ and $V_P$ with the updated system.

**The USP site**

The USP site profile basically can be divided into a brown clayey fine sand layer, Cenozoic Sediment with lateritic behavior (LA'), up to about 6 m depth that exhibits collapsible behavior upon wetting. Under this layer there are pebbles of about 0.5 m thick. The last layer is a residual soil from sandstone, red clayey fine sand with non-lateritic behavior (NA'). These soils are classified as SC in the Unified Soil Classification System (USCS). The MCT Soil Classification System (Mini, Compacted, Tropical) proposed by Nogami & Villibor (1981) for tropical soils was used to define and classify the soil with regards to its lateritic behavior. The groundwater table varies seasonally between 9 and 12 m below the ground surface.

Figure 7 shows the location of the tests carried out at the USP site and discussed in this paper. Figure 8 shows test data of four CPTus (CPTu 1, CPTu 2, CPTu 3 and CPTu 4), two cross-holes (CH 1 and CH 2), three SDMT and two down-holes carried out using the updated system (DH 1 and DH 2).

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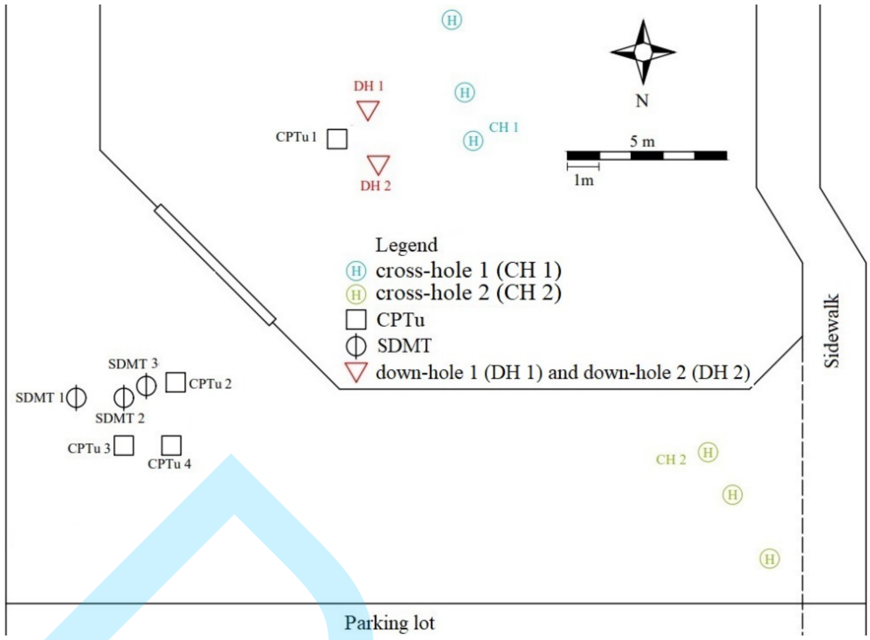


Figure 7: Location of in-situ tests carried out at the USP (São Carlos Campus) research site.

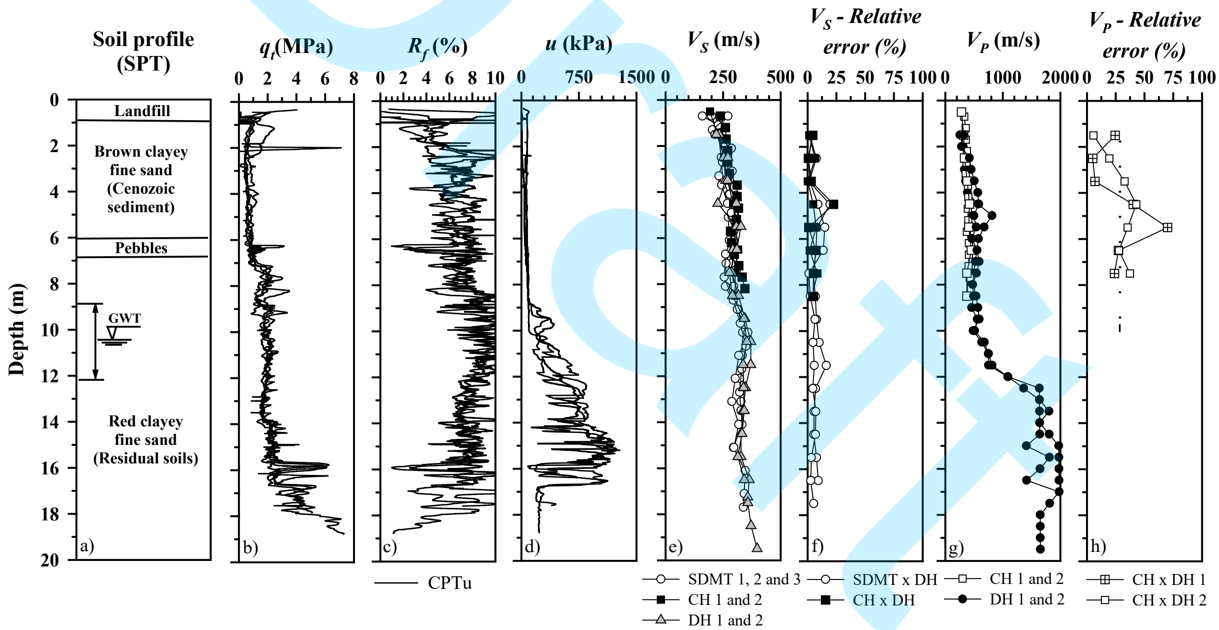


Figure 8: CPTu, cross-hole, SDMT and down-hole tests data at the USP site.

Figure 8a presents the soil profile defined by SPT. Figures 8b shows that the corrected cone resistance ($q_t$) assumes an almost constant value equal to 0.9 MPa up to about 7 m depth, 2 MPa between 7 and 16 m depth and 3.8 MPa from 16 to 18 m depth. While, for friction ratio, it assumes an average equal to 6% up to about 7 m depth and 8.2% from 7 to 18 m depth. Figure 8d shows excess pore pressure generated around the cone around 9 m depth, which can be an indication of the groundwater table. This depth is according to a monitoring well on USP site. Figure 8e shows the $V_s$ values measured by the updated system and by cross-hole and down-hole tests previously carried out at this site (Giacheti et al., 2006b).

Figure 8f shows that the average relative error (%) of the $V_S$ values determined by the updated system and by the down-hole (DH 1 and DH 2) and cross-hole (CH 1 and CH 2) tests was 8.4% and 6.5%, respectively. It can also be seen in this figure that the average relative difference between CH 1 and CH 2 was 7.9%, which is in the same range as that obtained with the updated system. Figure 8f also shows the similarity between $V_S$ determined by a commercial seismic dilatometer (SDMT) and the down-hole test using the updated system since the average relative error was 6.7%. It is worth noting that a greater difference was observed between 6 and 8 m depth. It may be related to interference from the pebble layer in the pathway of the seismic waves.

The updated system also allows $V_P$ to be determined. Figure 8g shows the $V_P$ values measured by the updated system (DH 1 and DH 2) and by cross-hole (CH 1 and CH 2) previously carried out at this site (Giacheti et al., 2006b). The average relative error between the down-hole with the updated system (DH 1 and DH 2) and average cross-hole tests (CH 1 and CH 2) was 28.5%, respectively (Figure 8h). It is important to mention that the interpretation of *P* waves was not possible to be done by the true interval method. It may be related to the rod waves influence in data acquisition, high-frequency noise as well as the non-perfect superposition of geophones locations and the oscillating nature of the arrival times in some soil layer intervals reflecting the lower resolution in time delay determination as discussed by Amoroso et al. (2020). Further tests are required to improve the quality of acquired *P* wave traces by improving the sensors response to increase reliability. In this sense, a commercial software (SPAS) was used to determined $V_P$ by the pseudo interval. Figure 9 shows the recorded traces with depth as well as the $V_P$ values for USP site after filtering the data.

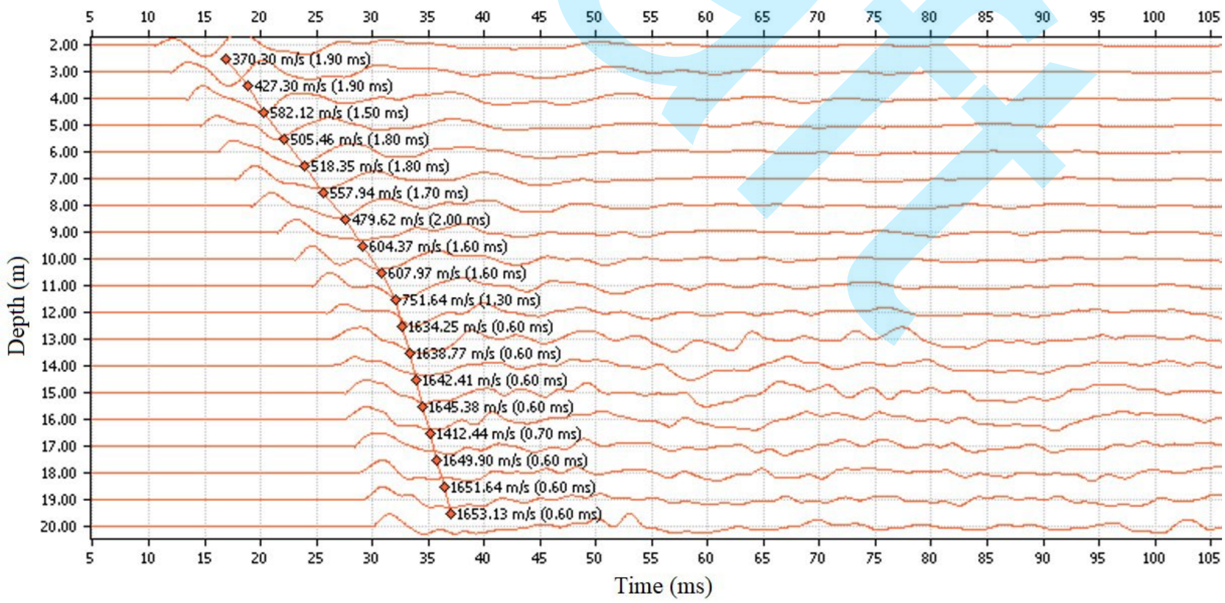


Figure 9: Seismic traces recorded to identify the first arrival of the *P* waves and the determination of the $V_P$ profile at the USP site.

Another possible application of $V_P$ is to differentiate fully or almost saturated soils from unsaturated soils, i.e. identifying the position of the groundwater table (Tsukamoto et al., 2002; Astuto et al., 2023) since saturated soils have higher *P* wave velocities than unsaturated ones. Normally, *P* wave velocities are less than 600 m/s in unsaturated soils and approximately 1500-1600 m/s below the groundwater table (Jamiolkowski, 2012; Gandolfo, 2022). The updated system was then utilized to estimate the groundwater table by determining the $V_P$ profile by the pseudo-interval technique using the commercial software SPAS.

Figure 8g shows an increase in $V_P$ to values above 1500 m/s at around 12 m depth. The groundwater table varies seasonally between 9 and 12 m below the ground surface at the USP site (Morais et al., 2020; Rocha, et al., 2021). The water level was determined at a depth of 10.45 m during the test campaign by means of a monitoring well. An increase in pore pressure was detected from a depth of 9.66 m in the *CPTu* carried out in the site (Figure 8d), which could also be an indicative of the presence of the water level. The difference observed may be related to the occurrence of capillary fringe. The thickness of the capillary fringe is directly proportional to the amount of fine-grained material present in the soil, i.e., the capillary fringe pressure is greater in clayey soils than in sandy soils (Gandolfo, 2022). It is important to mention the in the USP site the fine fraction content (silt and clay) is approximately equal to 35% (Pedrini et al., 2018).

**The Unesp site**

The soil profile at the Unesp site is a residual soil formed in the Quaternary covered by a lateritic (LA') red clayey sand (13 m thick colluvial soil – Neo Cenozoic sediment). These soils are classified as SM-SC in the USCS. Giacheti et al. (2019) described this research site as a porous and collapsible soil, the density increases with depth, with a high saturated hydraulic conductivity ($10^{-5}$ to $10^{-6}$ m/s) and with cohesive-frictional behavior. The water level is not found up to 30 m depth at this site.

Figure 10 shows the location of the in-situ tests carried out at the Unesp site. Figure 11 shows test data of three CPTus (CPTu 1, CPTu 2 and CPTu 3), four SDMT, one cross-hole (CH 1) and three down-hole tests carried out by the updated system (DH 1, DH 2 and DH 3). The cross-hole test was carried out about 300 m away from the SDMTs and DHs carried out with the updated system and the site profile is the same and has undergone the same pedogenic and morphogenetic processes that typically occur in tropical zones.

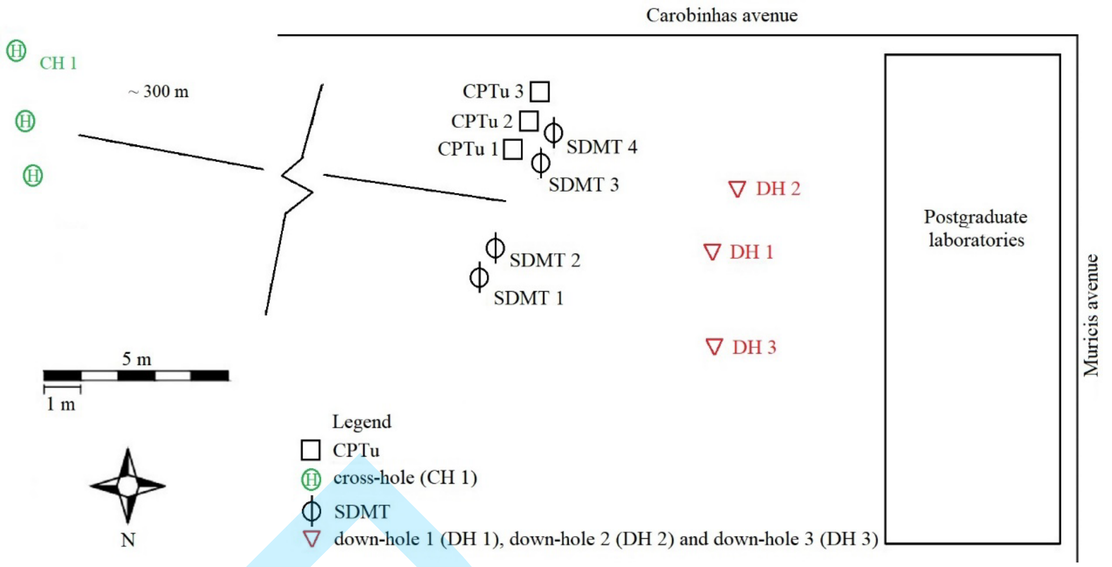


Figure 10: Location of in-situ tests carried out at the Unesp (Bauru Campus) research site.

Figures 11b and 11c show that the cone resistance ($q_c$) increases almost linearly with depth and the friction ratio ($R_F$) varies between 0.5 and 2.0%, respectively. Figures 11d and 11e allow comparing $V_S$ determined by the down-hole test using the updated system with those obtained from cross-hole and SDMT. It can be observed based on these figures that:

- The DH 1, DH 2 and DH 3 tests provided very similar $V_S$ profiles, with an average relative error of 5.6%, 5.9% and 4.6% respectively from average SDMT profile with little variation of this difference over the depth;
- The DH 1, DH 2 and DH 3 tests provided, respectively, an average relative error of 8.5%, 5.0% and 3.5% considering the results of the cross-hole test as a reference;
- It is important to note that when comparing the average results of SDMT with cross-hole, the average relative error was 6.4%. This value is equivalent to those obtained using the updated seismic system.

Figures 11f and 11g allow comparing $V_P$ determined by the down-hole test using the updated system with those obtained from cross-hole and SDMT. It can be observed based on these figures that:

- The DH 1, DH 2 and DH 3 tests do not provide similar $V_p$ profiles as observed for $V_s$. The average relative errors are respectively 25.8%, 29.5% and 15.2% from cross-hole;
- The observed differences may be associated with the lower resolution in determining the arrival time interval for *P* waves;
- Further studies and tests are therefore necessary to enhance the quality of the acquired *P* wave traces, improving the response of the sensors to increase the reliability of $V_p$ determination.

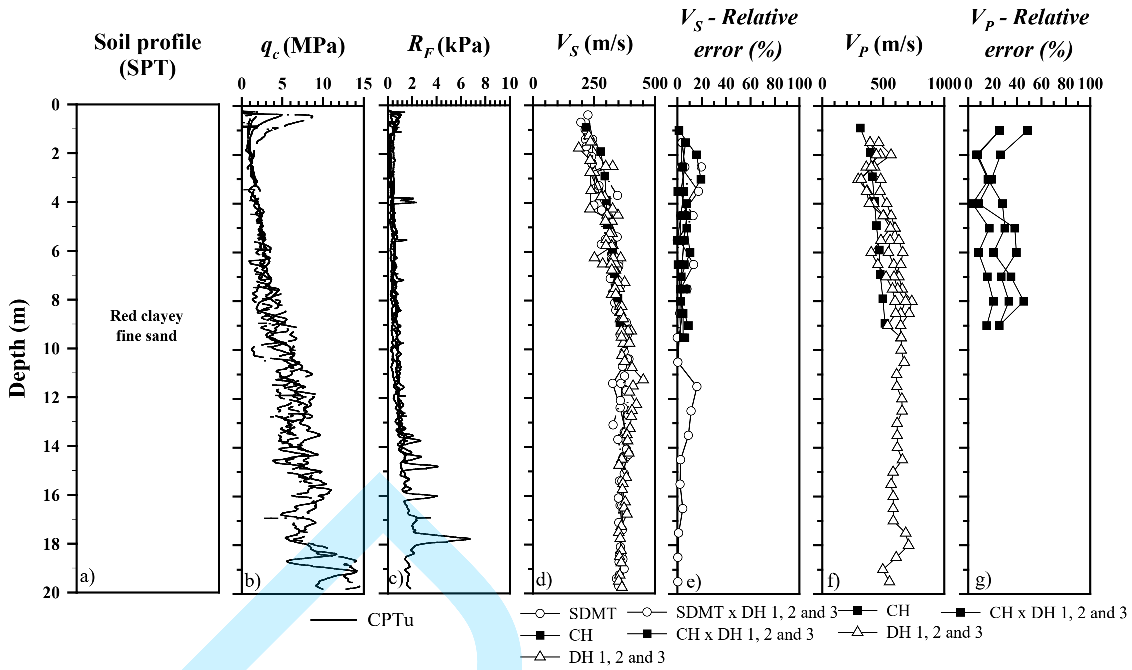


Figure 11: CPTu, cross-hole, SDMT and down-hole tests data at the Unesp site.

**Municipal Botanical Garden of Bauru**

Unfortunately, no SPTs have been performed at this site. Therefore, the three CPTu carried out were interpreted using the CPeT-IT software to define the site profile. CPeT-IT is software for *CPT* and *CPTu* data interpretation. This software allows the basic interpretation in terms of Soil Behavior Type (SBT) and various geotechnical soil and design parameters using current published correlations (Robertson, 2016). Figure 12 shows the location of the in-situ tests carried out at the site. Figure 13 shows test data of three CPTus (CPTu 1, CPTu 2 and CPTu 3) and five down-hole tests carried out using the updated system (DH 1, DH 2, DH 3, DH 4 and DH 5). Unfortunately, there are no SDMT and/or cross-hole to provide reference of $V_S$ and $V_P$ values for this site.

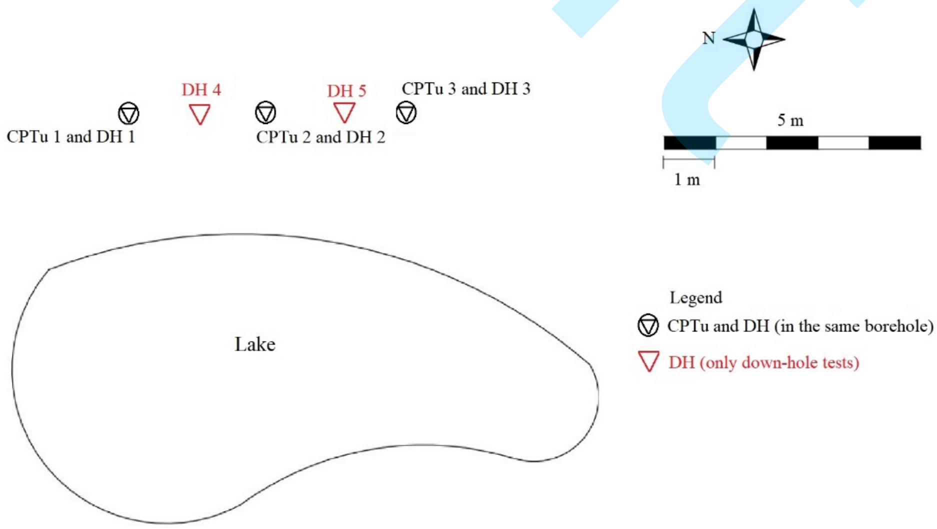


Figure 12: Location of in-situ tests carried out at the Municipal Botanical Garden of Bauru research site.

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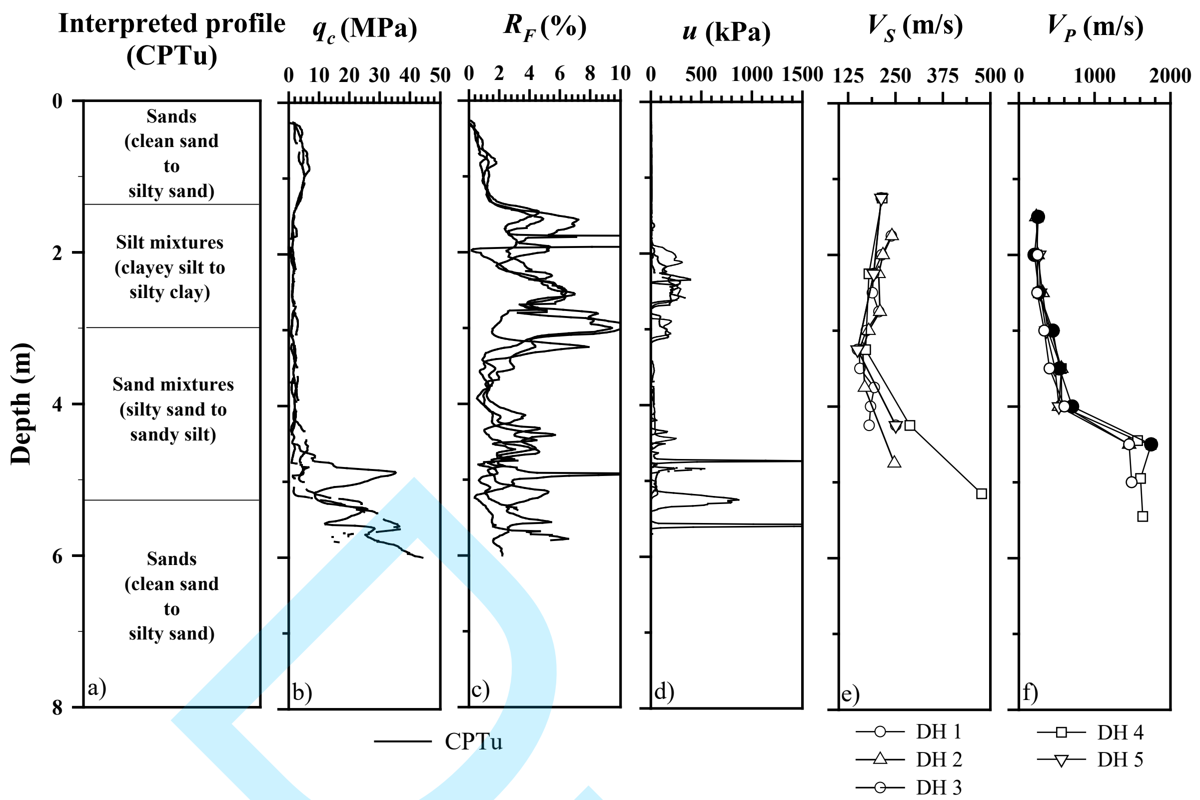


Figure 13: CPTu and down-hole tests data carried out at the Bauru Municipal Botanical Garden site.

The site profile defined based on CPTu at the Municipal Botanical Garden of Bauru indicated that a sandy soil (clean sand to silty sand) occurs from 0 to 1.4 m depth, silt mixtures (clayey silt to silty clay) from 1.4 to 3.1 m depth, sand mixtures (silty sand to sandy silt) from 3.1 to 5.2 m depth and sands from 5.2 m until the end of the test, approximately 6.5 m depth (Figure 13a). It can also be seen in this figure that there is an increase in cone tip resistance for the 3 CPTus, from a depth of around 5.4 m with the cone probe reaching the impenetrability (Figure 13b). Figure 13c shows different trends for the $R_F$ with average values of 1% on the top 1.2 m, 4% between 1.2 and 3.4 m, and 2.2% below this depth. Figure 13d shows that increases in pore pressure were detected between about 2 and 3 m depth, which is an indication of the possible presence of a water level below that depth. Figure 13e shows good repeatability among the $V_S$ profiles for the five down-hole tests, with a greater difference among tests for the determinations carried out from a depth of 4.3 m. Equivalent repeatability is also observed for the $V_P$ profiles, also with a greater difference from 4.3 m depth (Figure 13f).

It is interesting to note from the data of the five down-hole tests carried out at this site that the $V_P$ profiles show a contrast, i.e. $V_P$ values sharply jump to higher values, approximately 1550 m/s, from 4.5 m depth. This sudden increase in $P$ wave velocity is associated with soil saturation. However, the increase in $V_P$ values was observed about 1.5 m below where the water level is believed to be, in the same way as it was observed for the $V_P$ profiles determined at the USP - São Carlos site.

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## GROUNDWATER TABLE IDENTIFICATION

Identifying the groundwater table (GWT) and determining its depth by means of down-hole tests for the USP and Bauru Municipal Botanical Garden sites did not result in the exact position of the GWT, since the transition between the unsaturated and saturated zones is not a clear interface, but gradual, with variable width, as discussed by Gandolfo (2022). The possible factors that make it difficult to define the groundwater table could be:

- Variation in the degree of saturation (*Sr*): several authors (Astuto et al., 2023; Cordeiro et al., 2022; Molina-Gómez et al., 2023; Biot, 1956; Pasquet et al., 2015) showed that $V_P$ decreases sharply when *Sr* = 100% and goes to a *Sr* = 90% (Figure 14). So, if there are occluded air bubbles in the transition between the unsaturated and saturated zones, *Sr* will be lower than 100% and $V_P$ will be lower than 1500-1600 m/s.
- Presence of fines: the variation of $V_P$ with degree of saturation is more complicated in complex site profiles, for instance where there is a significant presence of fines, because in low permeability geomaterials, full saturation can be difficult to achieve due to an irreducible fraction of air the pores, limiting the maximum $V_P$ velocity (Fratta et al., 2005; Pasquet et al. 2015).
- Exclusive use of the $V_P$ profile: only the $V_P$ profile may be insufficient to obtain hydrological information (Pasquet et al., 2015; Gandolfo 2022). The combined use of *P* and *S* waves, in terms of $V_P/V_S$ index and Poisson's ratio (υ) can be used to reduce interpretation ambiguities. $V_P/V_S$ greater than 4 and Poisson's ratio (υ) greater than 0.45 characterize saturated soils (Pasquet et al., 2015; Thota et al., 2020).
- Identifying the first arrival of the *P* waves: accurately defining the *P* wave travel time is essential to calculate $V_P$. The most common approach to define the travel time is manually; however it is difficult on noisy signal records without a certain level of experience (Amoroso et al., 2020; Suwa et al., 2022). Seismic tests must therefore provide quality *P* wave records to increase the reliability of $V_P$ determination and their application in defining the *GWT*.

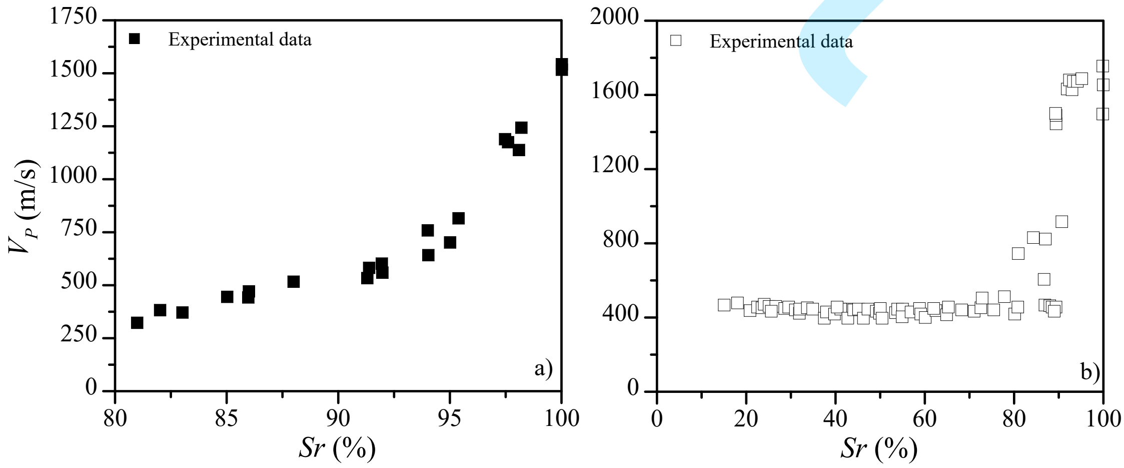


Figure 14: $V_P$ versus degree of saturation (*Sr*). a) adapted from Molina-Gómez et al. (2023) ; b) adapted from Leong & Cheng (2016).



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## CONCLUSIONS

This paper presented an updated version of a system to carry out the down-hole tests together with the piezocone penetration test to determine compression ($V_P$) and shear ($V_S$) waves velocities to improve the geotechnical site characterization. The tests carried out at three sites allowed to conclude the following:

- The updated software integrates data acquisition, allows visualization of the seismic traces and calculates the $V_S$ values by the true interval method. The results of down-hole tests interpreted with this software to determine the $V_S$ are equivalent to those interpreted using a commercial software. This software also allows the acquisition, visualization and storage of *P* wave recordings. $V_P$ can only be calculated by the pseudo time interval method using commercial software after acquiring all the data.
- The updated seismic probe can be used in saturated and unsaturated soils in conjunction with the piezocone test. It has six geophones, three for *S* wave recordings, spaced 0.5 m apart, and three for *P* wave recordings, also spaced 0.5 m apart.
- *S* wave velocity ($V_S$) was determined with the updated system by the true time interval as each stroke was applied. There was consistency between the $V_S$ profiles obtained by the updated system with SDMT and cross-hole tests in two sites.
- Determining the *P* wave velocity ($V_P$) with this system can only be done by the pseudo-time interval, after recording all *P* waves generated along the depth and employing commercial software. However, the differences between $V_P$ determined at the USP - São Carlos and the Unesp - Bauru sites were high considering the reference values of the cross-hole tests. It is therefore considered that this system is not yet fully reliable for determining *P* wave propagation velocity ($V_P$) profiles.
- The tests carried out at USP - São Carlos and the Municipal Botanical Garden of Bauru showed a contrast in $V_P$ close to the groundwater table, jumping abruptly to high values close to 1500-1600 m/s. Therefore, it is considered that the recording and interpretation of the *P* wave traces are sensitive to the presence of groundwater, but did not allow us to define the exact position of the GWT in these two sites. Further tests are needed to improve the quality of the *P* wave traces acquired by this system, to increase the reliability of the $V_P$ profile determinations.

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