Developing a System for Down-Hole Seismic Testing Together with the CPTU

O.P.M. Vitali, R.A.A. Pedrini, L.P.R. Oliveira, H.L. Giacheti

Abstract. This paper presents a system for performing down-hole seismic test together with the piezocone test in order to determine the shear wave velocity (*Vs*) and for calculating the maximum shear modulus (*Go*); a basic parameter for analyzing the dynamic soil behavior and a reference value of the soil stiffness. The system components are described and tests results for checking the geophone response are also presented, both before and after installation into the probe. The system was used in down-hole tests carried out at three experimental research sites located in the interior of Sao Paulo State, Brazil, where in situ seismic test results are available. The *Vs* values measured in down-hole tests carried out with this system were consistent with those determined in cross-hole tests and with a commercial seismic piezocone, which enabled to validate the developed system.
Keywords: site investigation, maximum shear modulus, down-hole, CPTU.

1. Introduction

The down-hole seismic test is considered as an alternative to the cross-hole technique; a much more expensive and time consuming test procedure. According to Robertson *et al.* (1986), down-hole and cross-hole testing provide equivalent results.

The Seismic Cone test was developed in the early 1980's and was first tried by a seismologist at the Long Beach office of then ERTEC (Campanella & Howie, 2005). After that, the results of an initiative by Fugro Inc. with the University of British Columbia, where seismic transducers were added to the piezocone, enabling simultaneous performance of the seismic down-hole test along with the traditional CPTU test (Robertson *et al.*, 1986). This new test, called the seismic piezocone penetration test (SCPTU) was a success, because seismic and CPTU test data are complementary. In a seismic test the soil stiffness is determined, not estimated by correlations, complementing the piezocone test results. Both tests results can be used to delineate the nonlinear stress – strain relationship of the soil through a modified hyperbola (Mayne & Schneider, 2000). Giacheti (2001) highlights the potential that the ratio Go/q_c has for the characterization of tropical soils. This ratio relates to the behavior of soil under small strains with its behavior under large deformations.

Despite the potential for interpretations from both down-hole and CPTU test results, in Brazil, there is not much test data on tropical soils, since the equipment available for performing seismic piezocone tests are mostly imported. This has caused difficulties for performing SCPTU tests due to the high cost, plus the delay for maintenance, repairing and calibrations, since these all depend on imported parts and services.

2. The System for Down-Hole Seismic Testing

The developed system has five components described as follows:

a) Machined steel probe which has three geophone compartments (0.5 m apart each);
b) Data acquisition system;
c) Software for data acquisition and interpretation;
d) Electrical trigger; and
e) Source for generating seismic waves.

The idea is to perform the CPTU test using a standard equipment and after that the down-hole seismic test is carried out driving a probe into the same borehole using our developed system. For this reason the diameter of the probe is greater than the standard cone. A description of each system along with their respective components and their tests and the test performance and data interpretations will be presented and discussed in this paper.

2.1. Test procedure

The test consists of pushing the probe continuously into the ground, the same way as it is done in a conventional piezocone test. At every 1 m a halt is made and the seismic testing is carried out. Shear waves are generated at the ground surface striking the source, which are captured by

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the geophones installed in the probe and the seismic data are recorded in a data acquisition system. The recommendations by Butcher *et al.* (2005) for performing these tests were followed.

During the preliminary tests of the system, the seismic probe spun with the addition of the rods. This rotation changed the axis of vibration of geophones affecting the quality of the recorded waves. This factor was considered to be the main cause for influencing the quality of the signals (Vitali *et al.*, 2010 and Vitali, 2011). This problem was solved by heavily holding the rods with a pipe wrench, preventing them from spinning during the operation of adding rods for pushing.

It was observed that those blows applied with great intensity generated waves of a higher amplitude and a lower quality than those generated from blows of a lower intensity (Vitali *et al.*, 2011). It is recommended to strike the source with less intensity, since it records waves with the main pulse of S waves free of distortions, which are easier to interpret.

2.2. Geophones

The three geophones are manufactured by Geospace Model GS-20DH OMNI. The main characteristics of these sensors include: 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, emphasising the importance of correct positioning of the geophones and keeping it so during the entire test.

Tests and calibrations were carried out in the laboratory to check if all three geophones matched the factory specifications, as well as seeing if they had the same response after installing them into the probe. This is fundamental for the interpretation by the true interval method (Butcher *et al.*, 2005). The test consisted of measuring the random vibrations produced by an electrodynamic vibrator with a geophone, an accelerometer and a laser dopler vibrometer (LDV), the measurements of which served as a reference for both sensors (accelerometer and geophone). The test results are shown in Fig. 1, where the transmissibility function, *i.e.*, the ratio between the geophone and accelerometer signals with respect to the LDV in the frequency domain, is used in order to verify the calibration factor of those sensors using a broad frequency band. As it can be seen the geophones presented an identical response consistent with the calibration curve supplied by the manufacturer.

As mentioned before, the response of the geophone and accelerometer were divided by the LDV signal, which is much more accurate and reliable, therefore the dimensionless value was obtained, which is known as transmissivity. It is important to mention that the accelerometer signal had to be integrated in order to obatin the same curve, which was done in the frequency domain. As a result

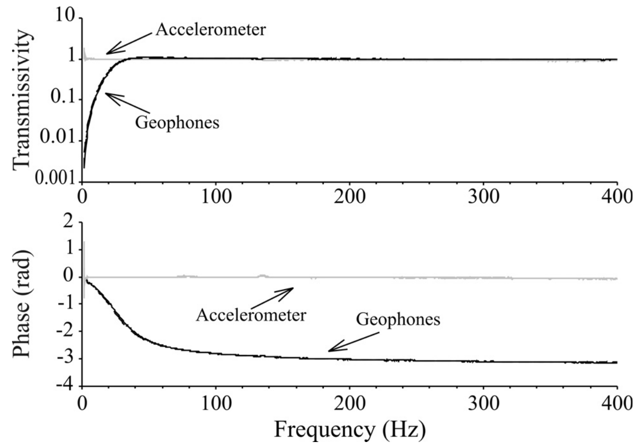

Figure 1 - Test results of the geophone calibration.

of the direct ratio of those two signals, the transmissibility (as any other transfer function or frequency response function) is a complex number, presenting amplitude and phase information. It was observed that for frequencies above 28 Hz, which is the natural frequency of the geophones, that the amplitude response for the three geophones is constant and identical to the response of the laser, hence transmissiblity equals one. According to Campanela & Stewart (1992), shear wave frequencies are between 40 Hz and 120 Hz, so these sensors are appropriate for their registration.

It is also important to notice that the transmissiblity analysis allows one to observe not only the amplitude but also the phase behaviour between the two signals. In this study, there was no difference between the phases of the three geophones used. Differences between the phases would indicate *delays* in the time domain, which compromises the use of the true interval method, described in item 2.9.

2.3. Seismic probe

A machined steel seismic probe was built with three compartments (0.5 m apart each) welded to two rods, for installation of the geophones in an uniaxial configuration (Fig. 2). In this manner, three recordings are registered at different depths for the same stroke, increasing the possibilities of testing interpretation and getting a more detailed *Vs* profile (at every 0.5 m interval). In a uniaxial configuration, it is essential to maintain the axis of vibration of the geophones parallel to the direction of the strike and maintain this position during the entire test; this factor is considered as the most important factor for the success of the test (Vitali *et al.*, 2010).

Tests were conducted in the laboratory to assess whether the installation of the geophones into the probe interferes with the quality of the recorded data. The probe was suspended with an elastic rope, simulating a free-free boundary condition, and accelerometers were installed under the geophone compartments, alligned with the geophones axis.

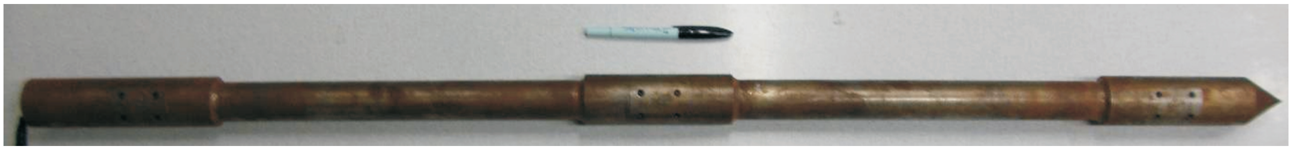

Figure 2 - Photo of the seismic probe.

The test was carried out by hitting each geophone's compartment with a small hammer instrumented with a load cell. Frequency response functions (FRF) of acceleration over force and geophone velocity over force were calculated and used to compare the geophone's dynamic behaviour with that of the accelerometer's behaviour.

The FRF relates the impulse, measured by the instrumented hammer, with the structure vibration, measured by the geophone fixed in the probe and by the reference accelerometer, therefore, identical FRFs mean that the geophones fixed in the probe present the proper response. Again, FRFs are also complex numbers, which present amplitude and phase behaviour and, differ from the transmissibility functions – used during the calibration phase – the FRFs could also provide some valuable information on the probe dynamics, such as its free-free resonances. Figure 3 shows a photo of the accelerometer attached to the geophone's compartment and Fig. 4 shows the testing data for comparing the response of the geophone with the accelerometer.

It can be seen in Fig. 4, that for frequencies higher than 30 Hz, the response of the geophones and accelerometers is essentially identical. The difference of 180° observed in the phase is due to the positioning of the sensors to the axis of vibration. It can therefore be concluded that the geophones installed into the probe provided reliable answers. It is worth mentioning that in the case of the other two compartments, the geophones also responded identically with the accelerometers.

Rubber o-rings were installed in geophone's compartment and liquid silicone was used in the connection with the rods. The probe was immersed in a PVC pipe filled with water and submitted to 750 kPa pressure for an hour to check the probe tightness. During this time, it was observed that there was no decrease in applied pressure, indicating no leakage and guaranteeing the probe water tightness.

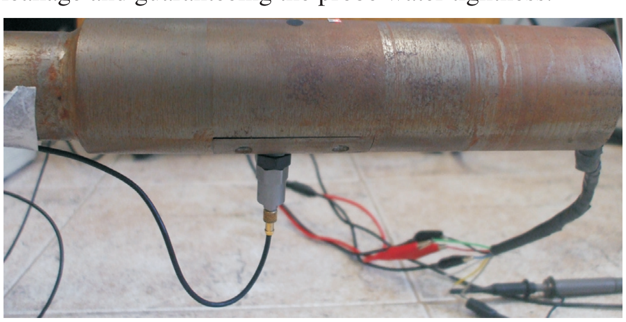

Figure 3 - Photo of the accelerometer attached to the geophone's compartment.

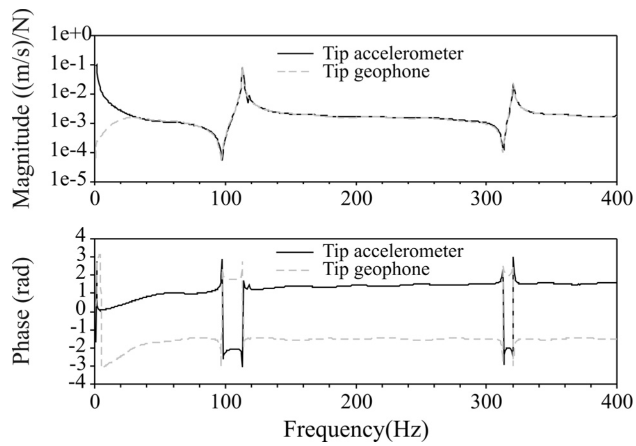

Figure 4 - Comparison between the FRFs of the geophone and accelerometer installed at the probe tip for the blow applied at the tip.

2.4. Data acquisition

Initially a 12 bit resolution with 16-channel analog-digital module was used for data acquisition. This equipment is the model ADS2000, with a signal conditioner model AI-2161, manufactured by Lynx Electronic Technology. The data acquisition software in Visual Basic was developed by Pedrini *et al.* (2010).

This system permits a maximum data acquisition frequency of 15 kHz, which is lower than the minimum value recommended by Butcher *et al.* (2005), which was 20 kHz. Although this data acquisition system presented a good performance it was replaced by another system from National Instruments; NI USB-6251 model. This device also has 16 channels but with a sampling rate of 1.25 MHz per channel and with 16 bit resolution. New software was developed for data acquisition and interpretation using the Labview platform. The decision for using this new system was the high capability it had for data acquisition with a relatively low cost. Two channels were used for each geophone to allow differential reading to enhance the recorded data quality. During the event, one channel provides the sensor signal plus noise while the other provides the inverted sensor signal plus noise. So, the recorded signal is the difference of the two signals, which corresponds to the duplicate sensor signal free of the noise. This approach is desirable but is not mandatory, as the noise can be removed with digital filtering. Figure 5 compares the field noise registered with differential and conventional reading, where the lowest noise intensity is noticeable for the differential reading.

According to the Sampling Theorem of Nyquist, the minimum sampling rate that does not corrupt the signal must be, at least, double of the existing maximum frequency in the signal (aliasing phenomenon).

Some data acquisition systems have an anti-aliasing filter, which prevents the registration of frequencies above half of the maximum sampling frequency of the board. However, the data acquisition system from National Instruments does not have an anti-aliasing filter, so it is essential to use a high sampling frequency in order to adequately sample the signal.

In two tests carried out in the experimental research site from Unesp, a sampling frequency of 40 kHz was used; double the minimum sampling frequency recommended by Butcher *et al.* (2005), and the results were corrupted due to aliasing phenomenon. It happened because this site is quite close to the meteorological radar station from Unesp (IPMet), which generates signals that interfer with the seismic wave records. In another test campaign carried out at the same site, this problem was avoided by using 150 kHz sampling frequency, which ensured an appropriate signal and an excellent resolution in time domain, fundamental for the application of the cross correlation method, described in item 2.9. Figure 6 shows a signal corrupted by the aliasing phenomenon. It is noteworthy that this phenomenon does not occur in this particular site using the data acquisition system from Lynx because it has an anti-aliasing analog filter on board.

2.5. Signal processing

Butcher *et al.* (2005) recommend recording the signal without any modifications. This recommendation was followed and then a digital filter (which does not cause delay on the signal) was used to remove noise.

The application of digital filter Butterworth low-pass type of third order with cutoff frequency of 400 Hz (corresponding to the spurious frequency of the geophones) completely removed the signal noise without distorting the main pulse of S waves, which occurs between the frequencies of 40 and 120 Hz (Campanella & Stewart, 1992). It provided a fairly reliable data interpretation (Fig. 7).

The software for data acquisition was prepared using the Labview platform. This software presents the original and filtered signal on the computer screen during the execution of the test, allowing visual inspection of signals before recording the data.

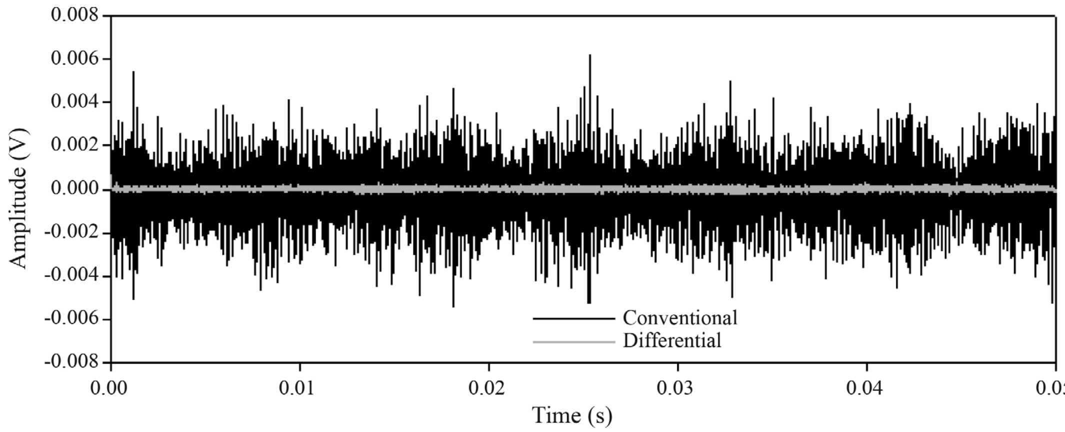

Figure 5 - Noise registered with differential and conventional reading in Unesp experimental research site using 100 kHz data acquisition frequency.

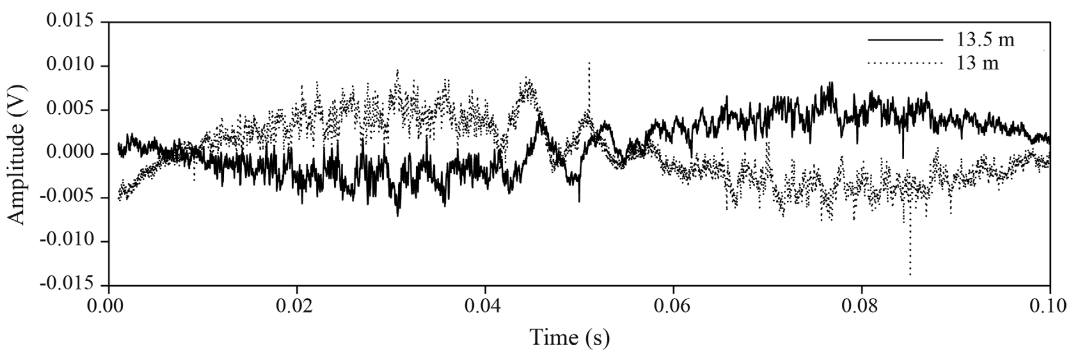

Figure 6 - Recorded signals at the Unesp experimental research site using 40 kHz data acquisition frequency, twice the recommended minimum frequency, which were corrupted due to the aliasing phenomenon.

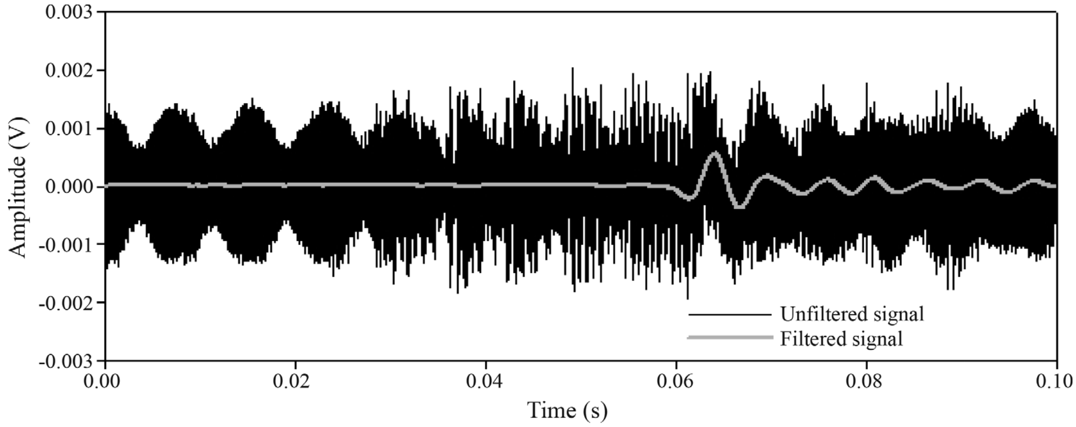

Figure 7 - Comparing the signal with and without the Butterworth low-pass digital filter of third order with a cutoff frequency of 400 Hz. Signal recorded at 20 m depth in the Unesp experimental research site using 150 kHz sampling frequency.

2.6. Trigger

The trigger device has the function of triggering the data acquisition system when the seismic event is generated. At the moment the hammer hits the seismic source, the circuit is closed and an electrical signal triggers the data acquisition system. After applying the strike, the trigger automatically resets itself for a new event. Campanella & Stewart (1992) compared several trigger devices and concluded that an electrical trigger is the simplest and most reliable device to be used.

2.7. Equipment for piezocone tests

A multi-purpose pushing device manufactured by Pagani Geotechnical Equipment was used to perform piezocone and seismic tests. This equipment has a pushing capacity of 150 kN and it is anchored to the ground by two 4 m long 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 for good quality of the recorded signals.

2.8. Seismic source

The seismic source consists of a steel bar placed on the ground by the pushing equipment, which is struck by a 2 kg sledgehammer. This type of source is suitable for generating predominantly S waves and allows generating reversed polarity waves striking both sides of the bar.

This source can be positioned behind or in the front of the pushing equipment. The rear leveling rod provides a higher vertical load than the front leveling rod ensuring a better contact with the ground, however, in the rear case, the source will be 1.8 m away from the hole and this horizontal distance will provide reliable *Vs* results only after 4 to 5 m depths are reached, as shown by Butcher & Powell (1996). These authors recommended the use of a horizontal distance less than 1 m between the seismic source and the borehole. When the source is placed in front of the pushing equipment, the horizontal distance is 0.3 m. In several tests, two seismic sources were placed, one in front and another in the rear of the pushing equipment in order to assess the best position for this source. Figure 8 shows a picture of the seismic source positioned in the rear of the pushing equipment and Fig. 9 show two graphics to compare the results with the waves generated simultaneously with the seismic source positioned in the rear of the pushing equipment (1.8 m) and at the front (0.3 m). The analysis of these data showed that in some tests higher shear wave velocities were calculated with the source 1.80 m from the hole up to about 6 m, as described by Butcher & Powell (1996). The *Vs* profiles obtained with the seismic source in the front were smoother, so this position was considered more appropriate and it was recommended for routine jobs. It is noteworthy that the closer the source is, the smaller will be the difference between the paths traveled by the waves ($L_1 - L_2$) (Eq. 1) of the spacing between the geophones, reducing errors associated with wave propagation in soil.

Figure 8 - Photo of the seismic source placed in the rear of the pushing equipment.

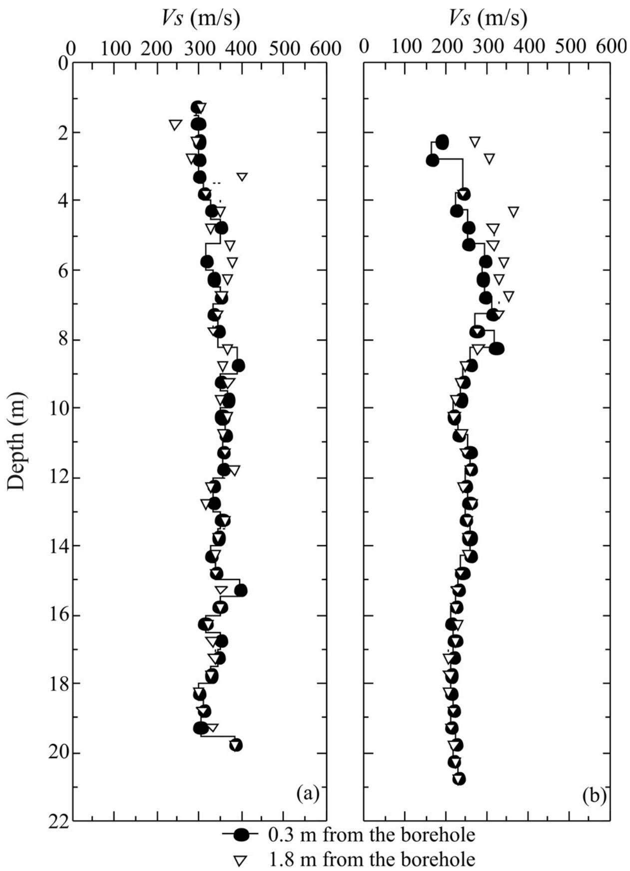

Figure 9 - *Vs* values calculated with the seismic source 0.3 m and 1.8 m from the borehole in tests conducted at the (a) Unesp experimental research site and at the (b) Unicamp experimental research site.

2.9. Data interpretation

The shear wave velocities (*Vs*) 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 from the source ($\Delta L = L_2 - L_1$). The difference between the distances traveled by the S waves, assuming a linear pathway, divided by the time interval provides the shear wave velocity (*Vs*), given by the Eq. 1.

$$V_s = \frac{L_2 - L_1}{T_2 - T_1} \quad (1)$$

Data interpretation was made using the cross correlation method, selecting a complete revolution of the main S wave pulse as recommended by Vitali *et al.* (2010). Details on the interpretation of down-hole seismic tests are presented by these authors. According to Campanela & 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 of 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, a software is necessary for data reduction and interpretation.

The true time interval is obtained recording the responses received by two sensors placed at two different depths resulting from 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 10 presents a schematic illustration of the true interval method.

Shear wave velocity values were calculated using data acquisition software developed by the use of the Labview platform. This software uses the cross correlation method and filters the signals from the three geophones. The *Vs* 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 for the data interpretation is almost simultaneous to the test execution, giving plenty of speed and convenience for the test.

The way the seismic probe was designed and built allows obtaining two *Vs* values with the geophones spaced 0.5 m and one *Vs* value with the geophones spaced 1 m for every single seismic event. Making the comparison of the results obtained using different geophone spacing was not found in any of the relevant literature on this subject. It was assumed that the results are similar and the use of smaller geophone spacing would be more appropriate because the waves would be more similar, facilitating the application of

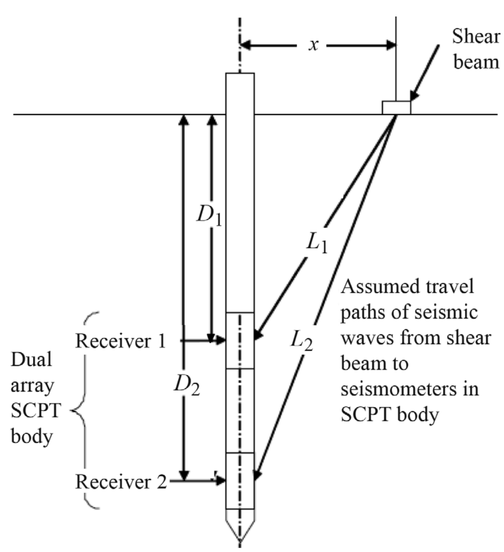

Figure 10 - Down-hole SCPT test with two seismic sensors at different depths (Butcher *et al.*, 2005).

the cross correlation method. The trajectory 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 11 demonstrates this comparison, which shows that the results were indeed equivalent.

3. System Validation

Several tests were conducted at the experimental research sites from Unesp, Unicamp and USP to validate the system. These sites were chosen because there is already cross-hole and SCPT test data available (Giacheti *et al.* 2006a; Giacheti *et al.* 2006b; Giacheti *et al.*, 2007) and this served as a reference for the comparison.

The tests performed at the Unesp and Unicamp experimental research sites used the National Instruments data acquisition system and the seismic source was positioned in front of the pushing equipment, 0.3 m away from the hole. The tests carried out at the USP experimental research site were carried out in 2009, a year before the others, the data acquisition system from Lynx was used and the seismic source were positioned in the rear of the pushing equipment, 1.8 m apart from the hole.

3.1. Unesp experimental research site

Giacheti (2001) describes the soil at the Unesp experimental research site, located in the city of Bauru, São Paulo, Brazil as a red sand clayey soil, classified as SM-SC. It is a porous and collapsible soil, the density increases with depth and the soil has a lateritic behavior up to about 13 m depth. Giacheti *et al.* (2006a) highlights the heterogeneity of the soil, observed throughout the electrical CPT testing data. Figure 12 shows the position of field tests conducted at this site, previously discussed in this paper.

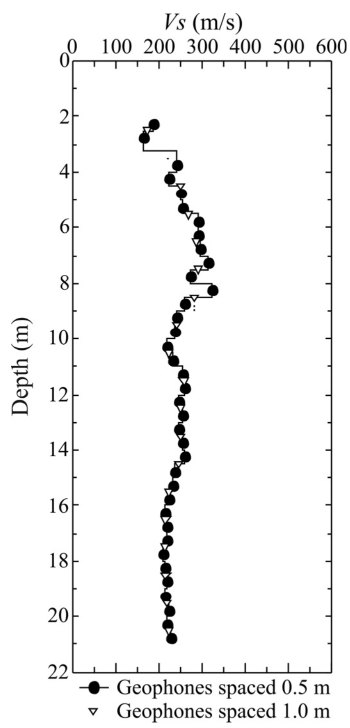

Figure 11 - *Vs* profiles with the geophones spaced 0.5 m and 1.0 m in tests carried out at the (a) Unesp experimental research site and at the (b) Unicamp experimental research site.

Some filtered signals obtained at different depths, during the down-hole test DH2 using the developed system are shown in Fig. 13. It demonstrates that all three different geophones provided signals with excellent quality. It is noteworthy that, in general, it is possible to get recordings of similar quality for all the three geophones.

Figure 14 shows the results obtained at this site for two cone tests (CPT1 and CPT2), a commercial seismic cone (SCPT), a cross-hole testing data (CH) and two down-hole tests carried out using the developed system (DH1 and DH2).

The DH2 test was carried out positioning the pushing equipment parallel to the alignment of the cross-hole test holes while the test DH1 was carried out perpendicular to this alignment, aiming to evaluate possible soil anisotropy.

Figure 14 also allows comparing down-hole test data using the developed system with those results obtained from other seismic tests using commercial equipment (cross-hole and SCPT). Considering the cross-hole and SCPT testing data, note that:

a) The DH1 test provided very similar results, with an average difference of 5.8% from cross-hole with little variation of this difference over the depth;

b) For the DH2 test results the average difference was 14.7% from cross-hole up to 7 m depth, and 5.9% from 7 m to 15 m depth; and

c) Comparing the SCPT test results with the cross-hole, the difference was 9.2% up to 10 m depth and 18.2 up to 15 m.

The observed differences were associated to soil heterogeneity in this particular experimental research site, as highlighted by Giacheti *et al.* (2006a), as well as possible soil anisotropy.

3.2. Unicamp experimental research site

The Unicamp experimental research site is located at Campinas, São Paulo State, Brazil. This site is basically composed of two distinct layers. The first layer extends up to about 6 m depth and consists of a red silty clay soil, porous, collapsible and with lateritic behavior. Below this layer there is a diabase residual soil with a clayey silt tex-

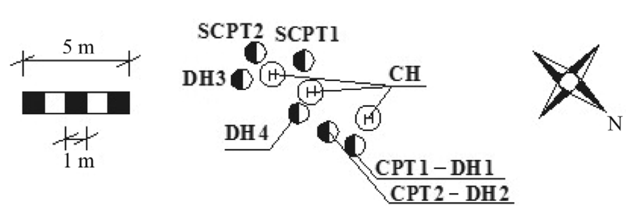

Figure 12 - Test locations at the Unesp experimental research site.

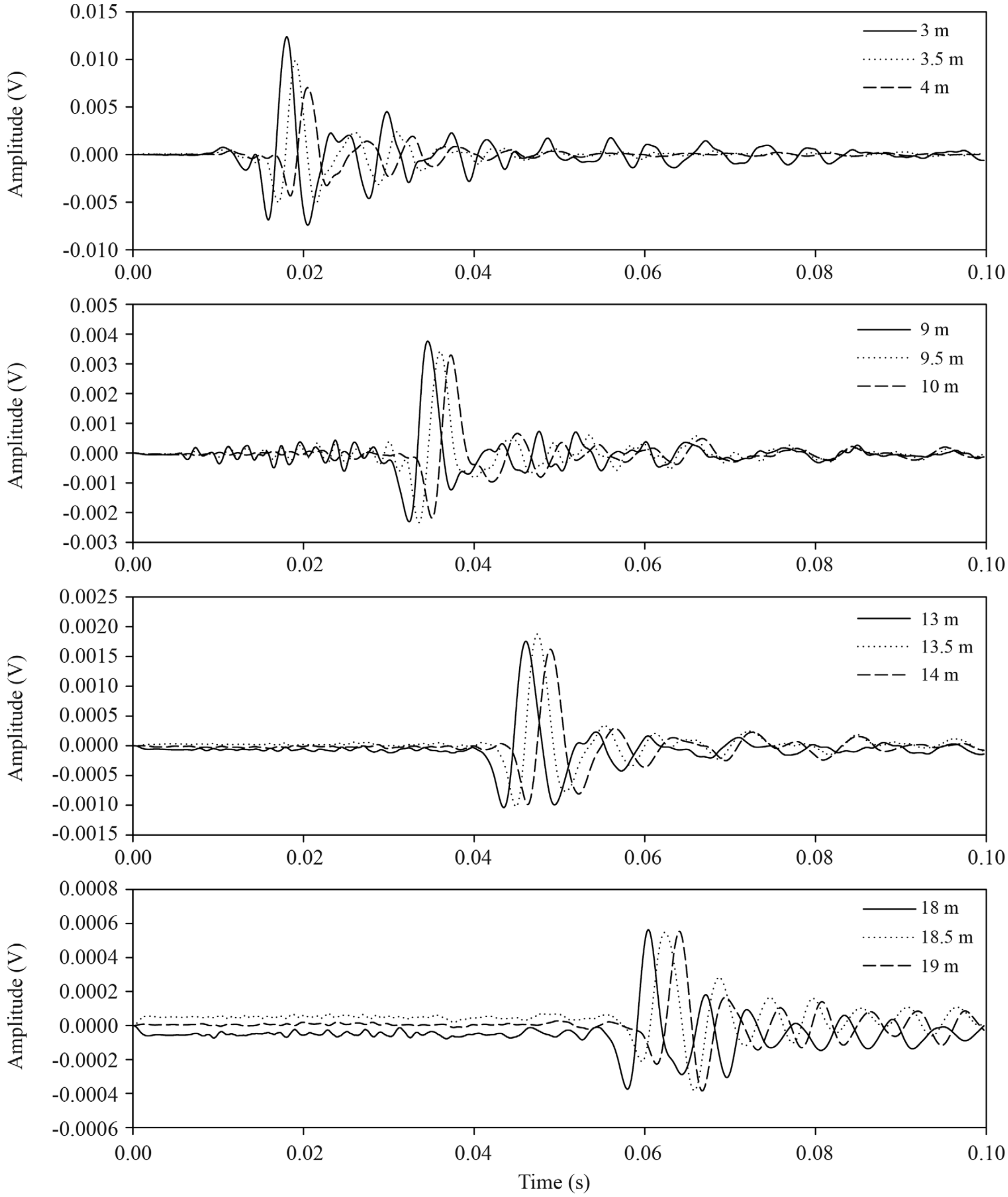

Figure 13 - Filtered signals using the developed system for down-hole seismic test (DH2) performed at the Unesp experimental research site.

ture (Giacheti, 2001). Figure 15 shows the location of field tests conducted at this site already discussed in this paper. The DH2 test was carried out up to around 7 m depth in a new experimental research site about 300 m away from where the other tests were performed.

Figure 16 shows results of two cone tests (CPT8 and CPT9), two commercial seismic cone tests (SCPT1 and SCPT2), a cross-hole test (CH) and one of the two down-hole tests (DH1) carried out using the developed system for the Unicamp site.

It is observed in Fig. 16 that the seismic test results had excellent consistency. There is a great dispersion of both the values of *Vs* and tip resistance (q_c), indicating a high local soil variability up to about 9 m depth. The average differences of down-hole test results DH1, DH2, SCPT1, SCPT2 compared with the cross-hole test result (CH) were respectively 22.4%, 19.4%, 9.3% and 14.8%. From 9 m to 17 m depth, where residual soil occurs, there is excellent consistency between the down-hole seismic test results SCPT1 and SCPT2 and for the DH1, with a mean

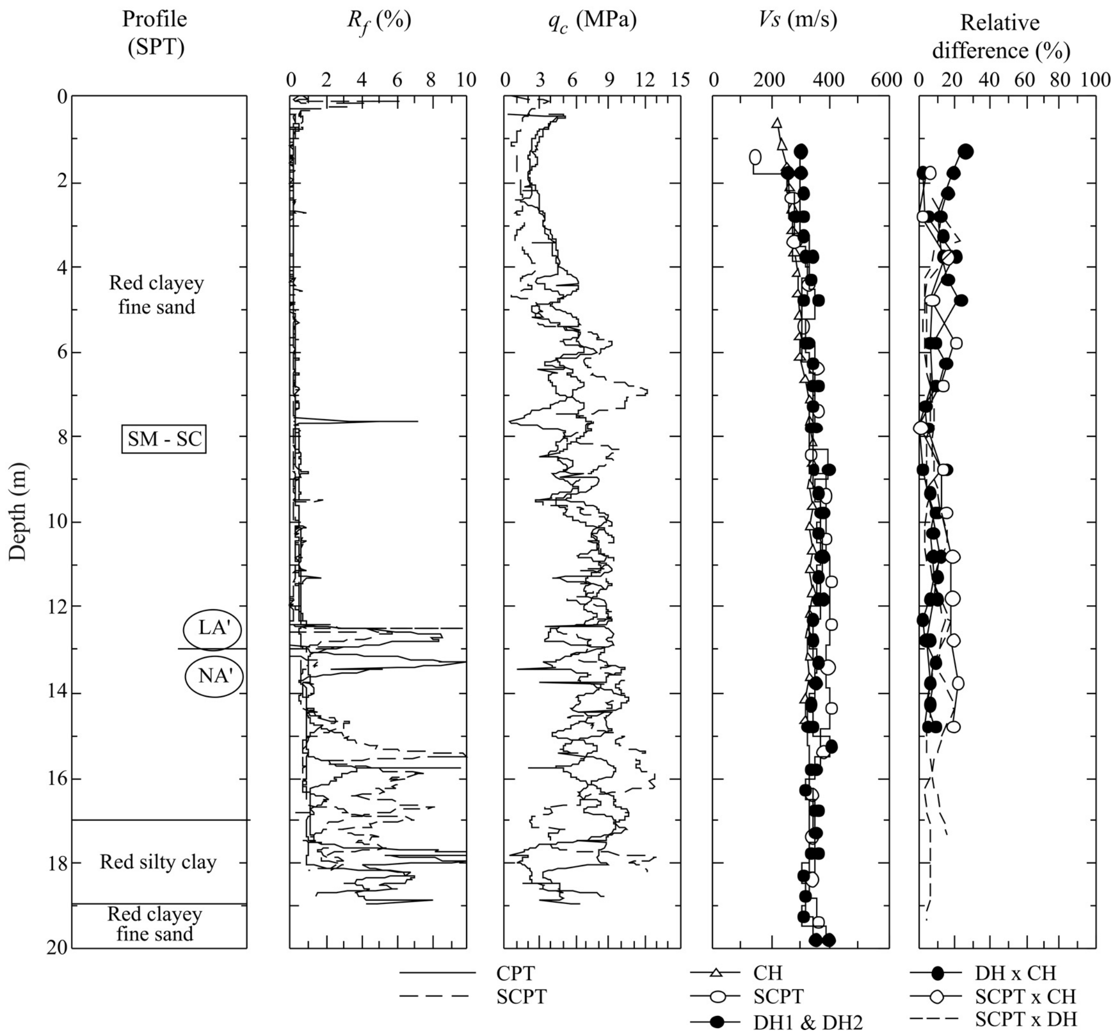

Figure 14 - CPT, cross-hole and down-hole tests results using commercial equipment and the developed system at the Unesp experimental research site. DH = down hole using developed system; SCPT = seismic CPT using commercial system; CH = cross hole using commercial system.

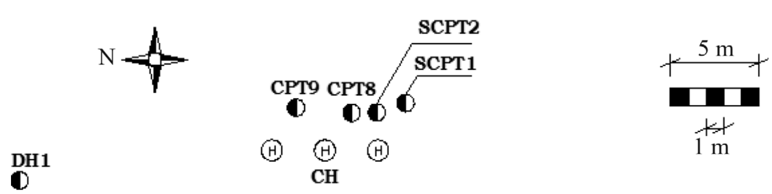

Figure 15 - Location of field tests carried out at the Unicamp experimental research site.

relative difference of 5.8%. Also noteworthy is the similarity of the results of q_c values in this region, indicating homogeneity of the geotechnical properties from this layer. After 17 m depth the cone reaches a silty fine sand layer, there is an increase in the relative differences of both *Vs* and q_c values and the average difference between the down-hole DH1 test result for the two seismic cone tests (SCPT1 and SCPT2) were 18.0% and 9.8%.

3.3. USP experimental research site

According to Giacheti (2001), the soils in this research site, located at São Carlos city, São Paulo State, Brazil, consist of a porous and collapsible clayey fine sand up to about 6.5 m depth, followed by a layer of residual soil of Bauru sandstone. These two distinct layers are divided by pebbles. Giacheti *et al.* (2006b) discussed the variation

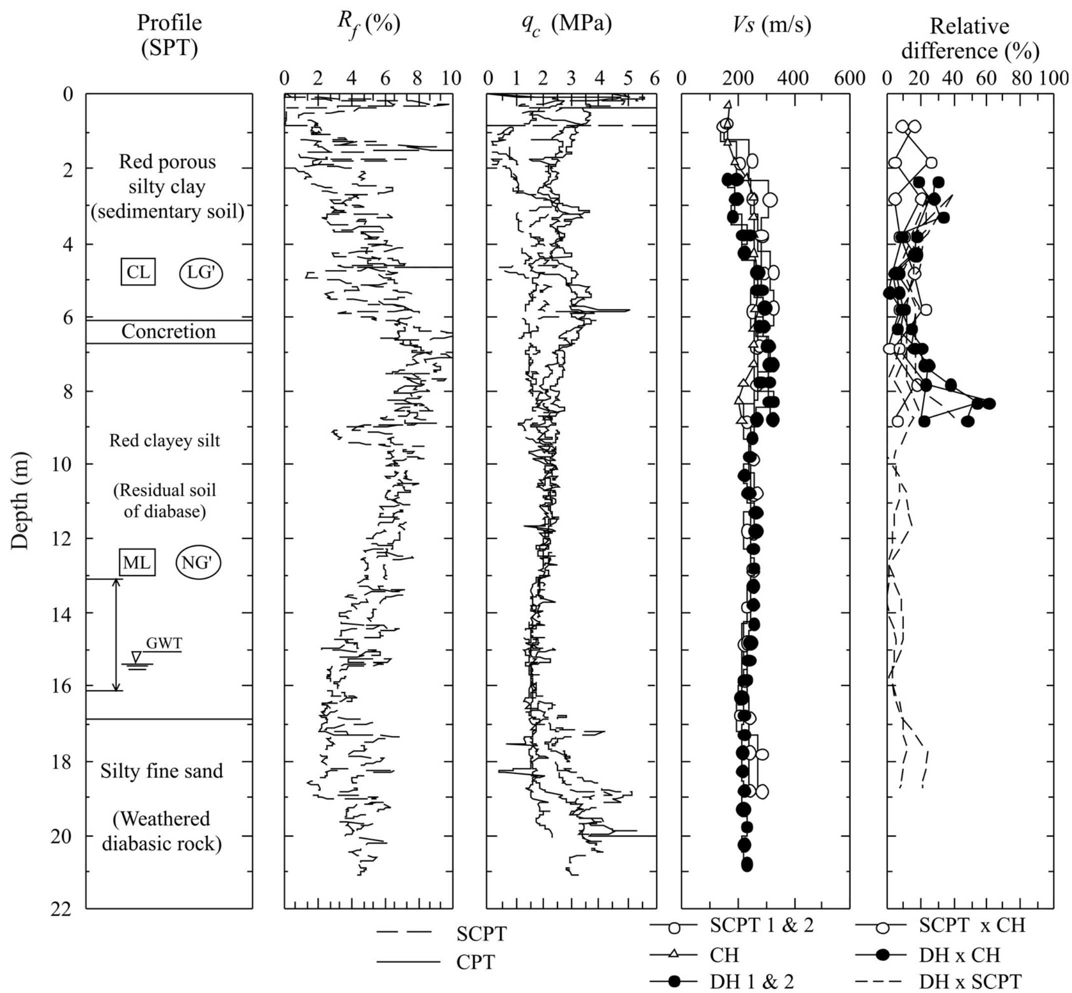

Figure 16 - CPT, cross-hole and down-hole tests results using commercial equipment and the developed systems at the Unicamp experimental research site. DH = down hole using developed system; SCPT = seismic CPT using commercial system; CH = cross hole using commercial system.

observed in the q_c and R_f values obtained in CPT tests conducted at this location. Figure 17 shows the location of the field test carried out at the USP research site and discussed in this paper. Figure 18 shows test results of three CPT tests (CPT1, CPT2 and CPT3), three commercial seismic cone tests (SCPT1, SCPT2 and SCPT3), two cross-hole tests (CH1 and CH2) and two down-hole tests carried out using the developed system (DH1 and DH2).

It can be observed in Fig. 18 that the average difference between the down-hole DH1 and DH2 test results, with the cross-hole CH1 test results was 7.7% and 6.3%, respectively. It is also possible to observe in this figure that the average relative difference from cross-hole CH2 and CH1 was 7.9%, which is in the same range obtained with the developed system, indicating that down-hole and cross-hole provide similar results at this site.

This similarity was not observed in the first 2 and 3 m depth points, probably because of the position of the seismic source, which was kept at a distance of 1.8 m away

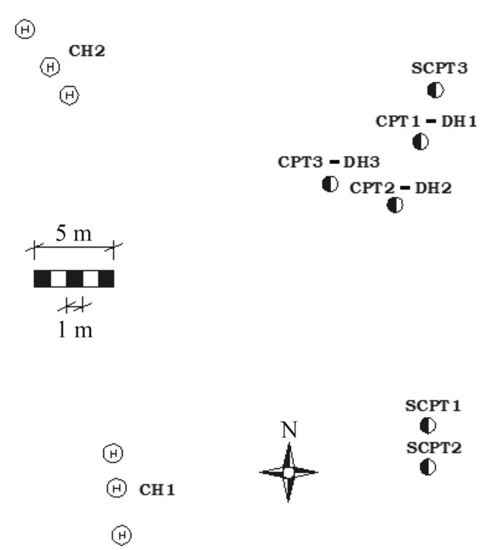

Figure 17 - Location of the field tests carried out at the USP experimental research site.

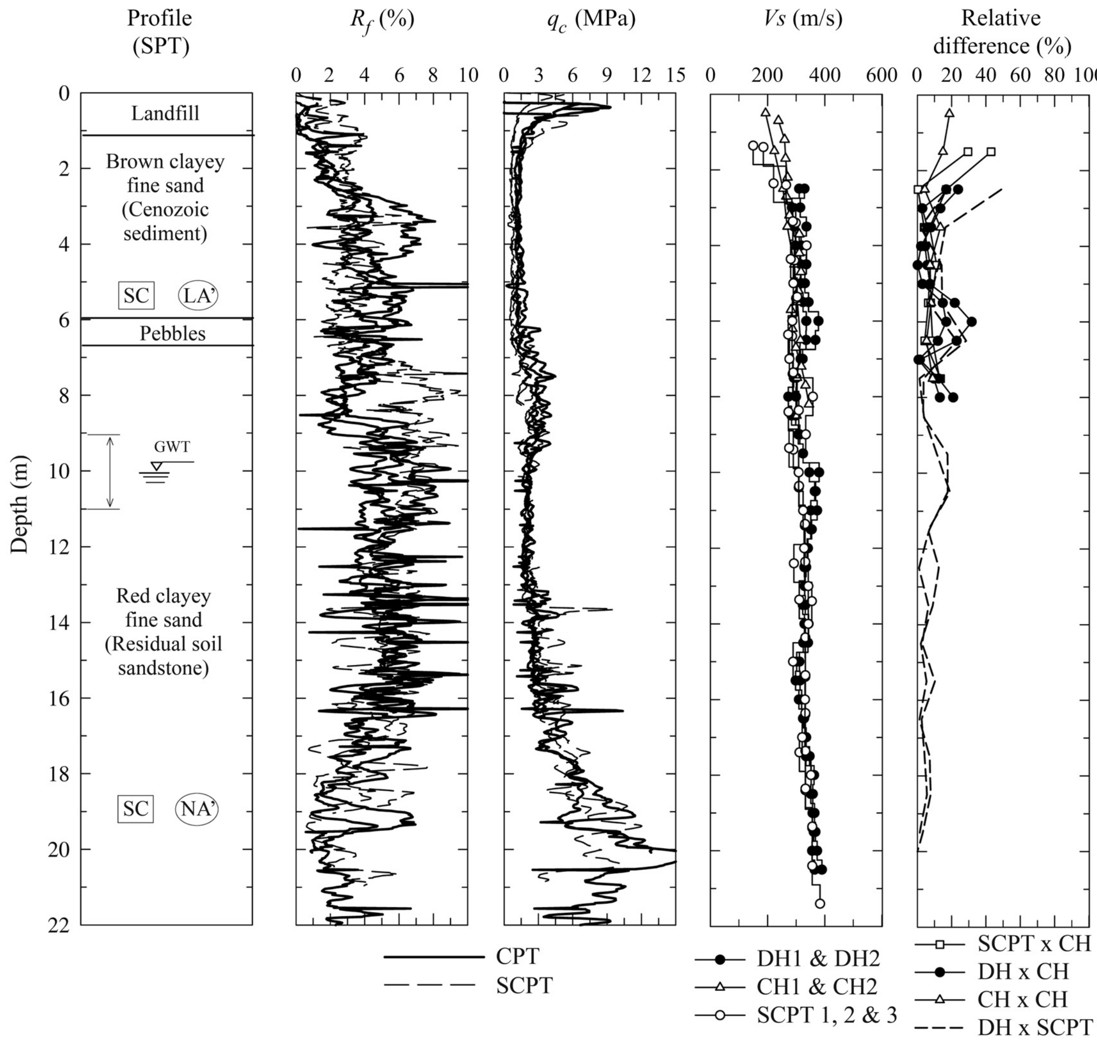

Figure 18 - CPT, cross-hole and down-hole tests results using commercial equipment and the developed systems at the USP experimental research site. DH = down hole using developed system; SCPT = seismic CPT using commercial system; CH = cross hole using commercial system.

from the hole. This difference was also observed in the pebble layer, between 5 and 7 m depth, where the average values between the DH1 and DH2 test results compared with the CH1 test were respectively 25.4% and 14.6%. It is important to point out that in this region the signals from the down-hole seismic tests had low quality, which was associated with interference from the pebble layer in the pathway of the seismic waves.

There are no cross-hole test results below 8 m depth. However, it was possible to verify the consistency between the *Vs* values calculated using the down-hole test with the developed system and with a commercial seismic cone (Giacheti *et al.* 2006b) since the average relative difference was 6%. The average results between 9 and 11 m depth were of 15.5%. This region corresponds to a zone of groundwater level variation, so considering that the tests were conducted at different seasons of the year; it is believed, based on our judgment, that this difference can be associated with a possible variation in soil suction, that could affect the soil stiffness and, consequently, the shear wave velocity.

4. Conclusions

The system developed for performing the seismic down-hole test right after and in the same hole of a CPT test proved to be very reliable.

The last version of the data acquisition software using Labview platform, which also includes interpretation using cross correlation and the true interval methods simultaneously to the testing execution was significantly improved. Using this software the later step of data processing and interpretation was eliminated through the test procedure becoming faster and easier to be conducted.

The laboratory test showed that the geophones have the same response and their installation in the seismic probe did not interfere in their seismic response, which is essential for using the true interval method.

The use of a seismic probe which has three geophones 0.5 m apart was very interesting because it allows obtaining a more detailed *Vs* profile, which is important for identifying different rigidity layers without requiring a longer test. The *Vs* values calculated with a spacing of 1 m and 0.5 m were considered similar.

The National Instruments data acquisition system and the developed software in the Labview platform were considered appropriate since this system presented a good performance at a relatively low cost. Since the data acquisition system does not have a low pass filter, the use of a high data acquisition frequency is necessary to avoid the aliasing phenomenon, which may compromise the test data. A high data acquisition frequency ensures an adequate sampling including the noise interference, which can be removed with digital filtering. Another possibility is to use an analog filter, which filters the signal at the time of acquisition; however, it should be verified that this filter does not cause delay in the signal arrival. The use of 150 kHz data acquisition frequency was considered adequate, ensuring appropriate sampling and an excellent resolution in time domain. This very high frequency is interesting for interpretation throughout the cross correlation method. It is recommended using the highest data acquisition rate allowed by the system in use and also a digital filter for noise removal.

The best results were obtained with the seismic source positioned in front of the pushing equipment, 0.3 m away from the hole, which can be considered consistent with the Butcher *et al.* (2005) recommendation. The seismic source closer to the hole makes the difference between the distances travelled by the seismic waves closer to the spacing between the geophones, reducing the error associated with the wave propagation pathways.

It was observed that the reliability of down-hole test results is directly related to the quality of the recorded signals, which heavily relies on the care taken during testing procedure and interpretation. The most significant factor for guaranteeing good quality seismic data was to keep the position of the axis of vibration of the geophones parallel to the blow direction. The recommended procedure is to secure with force the test rod using a pipe wrench, ensuring the maintenance of the correct position of the geophones during all tests. The intensity which the hammer hits the seismic source also influences the signal quality. It was observed that applying strokes with a lower intensity, generates the best waves, which are preferable because they facilitate all data interpretation.

The consistency between the results obtained in the down-hole tests conducted with the developed system with the results of SCPT tests performed with commercial equipment and with those obtained in cross-hole tests allowed validation of the system.

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References

Butcher, A.P.; Campanella, R.G.; Kayne, A.M. & Massarch, K.R. (2005) Downhole seismic cone procedure to measure shear wave velocity - The guideline. The International Society for Soil Mechanics and Geotechnical Engineering, Technical Committee No. 10: Geophysical and Geotechnical Engineering Testing, 5 pp.

Butcher, A.P. & Powell, J.J.M. (1996) Practical considerations for field geophysical techniques used to ASSESS ground stiffness. Advances in Site Investigation practice. Thomas Telford, London, pp.701-714.

Campanella, R.G. & Howie, J. (2005) A Practical Applications of the Cone Penetration Test, a Manual on Interpretation of Seismic Piezocone Test Data for Geotechnical Design. U.B.C. Civil Engineering Department, 305 pp.

Campanella, R.G. & Stewart, W.P. (1992) Seismic cone analysis using digital signal processing for dynamic site characterization, Canadian Geotechnical Journal, v. 29:3, p.477-486.

Giacheti, H.L. (2001) Field Tests in Site Investigation: Study and Considerations to the Applicability for Tropical Soils (in Portuguese). Associate Professor Thesis, Faculty of Engineering, Unesp, Bauru, 301 pp.

Giacheti, H.L.; De Mio, G.; Dourado, J.C. & Malagutti, W. (2006a) Comparing down-hole and cross-hole seismic tests results on the Unesp Bauru experimental research site (in Portuguese). Proc. XIII Brazilian Congress of Soil Mechanics and Geotechnical Engineering, Curitiba, v. 2. pp. 669-674.

Giacheti, H.L.; De Mio, G. & Peixoto, A.S.P. (2006b) Seismic cross-hole and CPT Tests in the Tropical Soil Site. Proc. ASCE GeoCongress, Atlanta, CD-Rom, pp. 1-6.

Giacheti, H.L.; Peixoto, A.S.P. & De Mio, G. (2007) Cross-hole and SCPT tests in a tropical soil from Campinas, SP, Brazil. Proc. XIII Panamerican Conference on Soil Mechanics and Geotechnical Engineering, Isla Margarita, CD-Rom, pp. 1-6.

Mayne, P.W. and Schneider, J.A. (2000) Evaluating axial drilled shaft response by seismic cone. Foundations & Ground Improvement, GSP 113, ASCE, Reston, pp. 655-669.

Pedrini, R.A.A.; Vitali, O.P.M. & Giacheti, H.L. (2010) Software for analysis of seismic records in down-hole tests with the seismic piezocone (in Portuguese). Proc.

XV Brazilian Congress of Soil Mechanics and Geotechnical Engineering, Gramado, CD-Rom, pp. 1-8.

Robertson, P.K.; Campanella, R.G.; Gillespie, D. & Rice, A. (1986). Seismic CPT to measure in-situ shear wave velocity, Journal of Geotechnical. Engineering, ASCE, v. 112:8, p. 791-804.

Vitali, O.P.M.; Pedrini, R.A.A. & Giacheti, H.L. (2010) Factors affecting the determination of maximum shear modulus in down-hole seismic tests with piezocone (in Portuguese). Proc. XV Brazilian Congress of Soil Mechanics and Geotechnical Engineering, Gramado, CD-Rom, pp. 1-8.

Vitali, O.P.M.; Pedrini, R.A.A. & Giacheti, H.L. (2011) Shear wave velocity in down-hole seismic tests: Equipment and factors affecting the test data. Proc. 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, 2011, Toronto, CD-Rom, pp. 1-7.

Vitali, O.P.M. (2011) Developing a System for Down-Hole Seismic Test Together with the Piezocone (in Portuguese). M.Sc. Thesis, Departamento de Geotecnia, Escola de Engenharia de São Carlos, São Carlos, 114 pp.