Shear wave velocity in down-hole seismic tests: Equipment and factors affecting the test data

Osvaldo Paiva Magalhães Vitali
USP-EESC, São Carlos, São Paulo, Brazil
Rubens Antonio Amaral Pedrini and Heraldo Luiz Giacheti
UNESP-FEB, Bauru, São Paulo, Brazil

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ABSTRACT
The maximum shear modulus (Go) is an important dynamic soil parameter in the geotechnical engineering design that can be calculated based on the shear wave velocity (Vs) measurement. Cross-hole and down-hole tests can be used to measure Vs. According to the literature, the seismic piezocone test has proven to be a fast, economical and reliable method to determine Go. It is assumed that down-hole and cross-hole tests have similar results. This paper briefly describes a system developed to perform the down-hole test right after the CPTU, using the same hole. In spite of all the advantages of down-hole tests, recording and interpretation of seismic data are not so simple. The test procedure and its interpretation for the developed system are presented herein to ensure the quality of measured Vs values, pointing out the most concerning aspects of the test.

RESUMEN
El módulo de corte máximo (Go) es un parámetro dinámico de los suelos importante en diseños geotécnicos que se puede calcular a partir de la medida de la velocidad de la onda de corte (Vs). Los ensayos cross-hole y down-hole pueden ser utilizados para medir Vs. De acuerdo con la literatura, los ensayos de piezocone sísmico se han mostrado un método rápido, económico y confiable para determinar Go y se puede asumir que los ensayos down-hole y cross-hole conducen a resultados similares. En este artículo se describe brevemente un sistema desarrollado para realizar ensayos down-hole luego después de la realización de un ensayo CPTU, utilizándose la misma perforación. A pesar de todos los beneficios de lo ensayo down-hole, el registro y la interpretación de dados sísmicos no son tan sencillos. En este trabajo, se presenta el procedimiento del ensayo y su interpretación para el sistema desarrollado para garantizar la calidad de los valores de Vs medidos, destacándose los aspectos más preocupantes del ensayo.

1 INTRODUCTION

The main purpose of the down-hole seismic test is to measure the shear wave velocity (Vs), and throughout the Theory of Elasticity, determine the maximum shear modulus (Go) of the soil, which is recognized as a reference parameter in geotechnical engineering, since it is the maximum stiffness that the soil can achieve. This parameter is essential in analysis of dynamic behavior of soils and foundations.

In the early 80s, seismic transducers were incorporated in a standard piezocone (Robertson et al, 1986), allowing the simultaneous execution of the traditional CPTU and the down-hole seismic test. Then, a "*hybrid test*", termed seismic piezocone penetration test (SCPTU) was created. The SCPTU is a logging test method to define soil stratigraphy and seismic and geotechnical parameters. A pre-drilling and casing is not necessary in the down-hole test with the SCPTU and it ensures a perfect contact between the sensor and the surrounding soils which is essential to properly performing a seismic test.

The accurate Vs measurement is essential for a reliable assessment of Go, since the shear wave velocity is squared to calculate this parameter (equation 1), where Go is the maximum shear modulus; Vs the shear velocity; γ the total unit weight and g the acceleration of gravity. Rodrigues et al. (2006) highlights that an error in Vs measurement causes an error two times greater in the calculated Go value.

$$Go = \frac{\gamma}{g} Vs^2 \qquad (1)$$

2 V_S MEASUREMENT

2.1 Time interval method

The time interval (T_2–T_1) is the difference between the arrival time of seismic waves to the transducers at two distances (L_1 and L_2) of the seismic source (Butcher et al., 2005). The difference between the distances covered by the S waves, assuming a linear path, divided by time interval provides the shear waves velocity (Vs) given by equation (2). Figure 1 illustrates this method.

$$V_S = \frac{L_2 - L_1}{T_2 - T_1} \qquad (2)$$

The time interval can be determined using two transducers located at different depths (true interval velocity) or using only one transducer positioned at different depths consecutively (pseudo interval velocity) (Butcher et al., 2005). The true interval velocity has the advantage of eliminating the errors associated with the trigger device and also eliminates the differences between the generated shear waves and inaccuracies in reading depths. True interval velocity requires the use of identical transducers. According to Campanella and Stewart (1992), the pseudo interval provides the same results that the true interval would provide when the trigger device is accurate and repetitive.

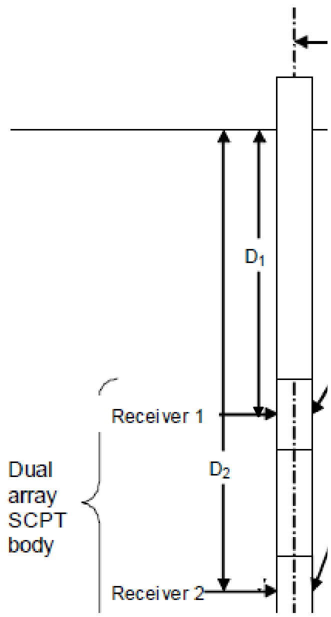

Figure 1. Down-hole CPT test with two seismic sensors positioned at different depths (Butcher et al., 2005).

2.2 Methods for Vs determination

There are basically three methods to determine Vs, as described below.

2.2.1 First arrival

In this method, the arrival time of the seismic wave is referenced to a remarkable point of the signal, such as a peak. This is a purely visual technique, being very subjective and highly dependent upon the signal quality. (Sully and Campanella, 1995).

2.2.2 Cross-over

This method consists in overlapping two signals with reversed polarities recorded at the same depth, obtained by applying strokes at opposite ends of the shear beam. This method cannot be used with an explosive source, because in this case it is impossible to produce waves with reversed polarity.

The crossing between the waves is the reference of the arrival time. Several authors, such as Butcher et al. (2005) and Campanella and Stewart (1992), suggest using the first crossing point, because it is easily identifiable and does not suffer the effects of signal attenuation and dispersion. Figure 2 illustrates a perfect cross between the waves.

This method considers only the information from one point of the entire recorded signal and cannot be applied if there are distortions in the signal at the intersection region or if there is a relative displacement between the waves (Campanella and Stewart, 1992).

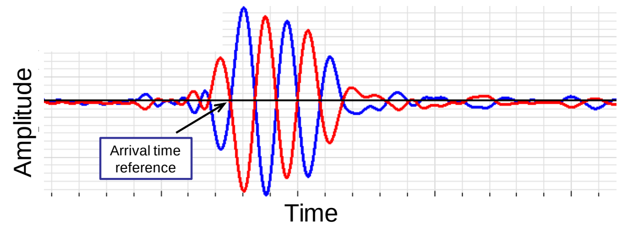

Figure 2. Application of the cross-over method.

2.2.3 Cross-correlation

This method overcomes the limitations of the other methods previously discussed because it uses the whole recorded signal to determine Vs. Campanella and Stewart (1992) highlight that it is not affected by localized distortions in the signal and it is considered the most reliable and consistent method. However, it is a more complex method and it requires the use of software.

According Campanella and 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".

Since this method uses the entire signal to perform the Vs calculation, the wavelets before and after the main pulse of the S wave should be removed because it interferes on the data interpretation. Campanella and Stewart (1992) recommend selecting a full revolution of the main pulse of the S waves. Figure 3 illustrates this procedure.

3 THE DEVELOPED SYSTEM FOR DOWN-HOLE SEISMIC TEST

The description of the developed system is presented in detail by Vitali (2011) and a brief description is presented as follows.

Seismic probe: A machined steel seismic probe was built with three compartments welded to two rods, 0.5 m apart, to install three geophones in a uniaxial array. This way, three traces are recorded at different depths for a unique stroke, increasing the possibilities of testing interpretation and getting a more detailed Vs profile (every 0.5 m interval). The probe was developed to perform the seismic down-hole test right after and in the same hole of a CPTU test.

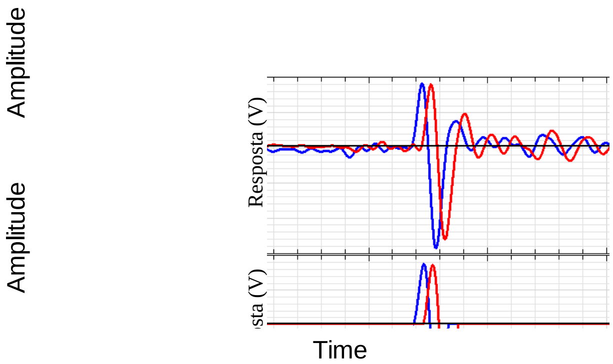

Figure 3. Selection of the main pulse of the S waves.

Seismic sensors: Three geophones manufactured by Geospace Model GS-20DH OMNI were used. 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, underscoring the importance of properly positioning the geophones and keeping them during the test. Campanella and Stewart (1992) achieved excellent results using similar geophones.

Seismic source: The seismic source consists of a shear beam loaded against the ground by the leveling pad of the pushing equipment which is struck by a 2 kg sledgehammer. This type of source is suitable to generating predominantly S waves. It also allows generating waves with reversed polarity striking both sides of the shear beam. Shear beams with of different sizes and at different distances from the test hole were tested.

Trigger: The trigger device starts the data acquisition system when the seismic event is generated. At the instant the hammer hits the seismic source, the circuit is closed and an electrical signal triggers the data acquisition system. After applying the stroke, the trigger automatically resets to a new event. Campanella and Stewart (1992) compared several trigger devices and concluded that an electrical trigger is the most simple and most reliable device to be used.

Data acquisition system: A National Instruments NI USB-6251 model was used. This device has 16 channels with a sampling rate of 1.25 MHz per channel and with a 16 bit resolution. A software developed with Labview platform was used for data acquisition and interpretation.

Pushing equipment: A multi-purpose pushing device manufactured by Pagani Geotechnical Equipment was used to perform the CPTU and seismic tests. This device has a pushing capacity of 150 kN. It is anchored to the ground by two 4 m long anchors, allowing a fast execution of the test, eliminating the need of drilling a lined hole. It is noteworthy that pushing the seismic probe into the ground ensures a perfect contact between the sensors inside the probe and the surrounding soil, which is fundamental to ensure good quality of the recorded signals.

4 FACTORS AFFECTING THE QUALITY OF RECORDED WAVES

It was observed during the tests that the orientation of the geophones and the intensity of the stroke were the factors that most influenced the S wave quality.

4.1 Geophone orientation

The axis of stroke and geophone must remain parallel to each other for maximum signal output. In some tests the seismic probe rotated in the ground due to the addition of rods. This rotation changed the axis of vibration of the geophones degrading the quality of the recorded traces. This fact was considered to have influenced the most on the quality of signals (Vitali et al, 2011). Figure 4 shows two signals, one with the geophone aligned parallel with the direction of the stroke and the other not aligned. This problem was solved by strongly tightening the rods with a pipe wrench, to avoid rotating during the pushing. Campanella and Howie (2008) sugest marking on the top front face of each rod with a felt pen after tightening it to help the operator to check for rotation.

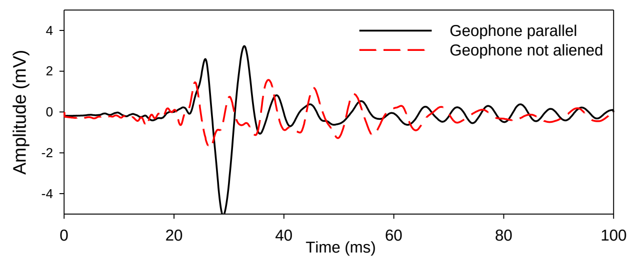

Figure 4. Recorded traces with the geophone orientation parallel and not aligned to the direction of the stroke.

4.2 Stroke intensity

Waves from strokes of greater and lower intensity were recorded to evaluate the quality of the recorded traces. Figure 5 presents traces obtained at Unesp – Bauru experimental research site to compare the results using different stroke intensities. The shear beam stroked by the hammer with greater intensity generated waves with higher amplitude and lower quality than those generated with lower intensity. This fact was attributed to excessive vibration of the shear beam by applying stronger strokes, dissipating the energy instead of transferring it to the ground. So, it was considered more appropriate to apply strokes of lower intensity, aiming to acquire a better quality signal to facilitate the interpretation.

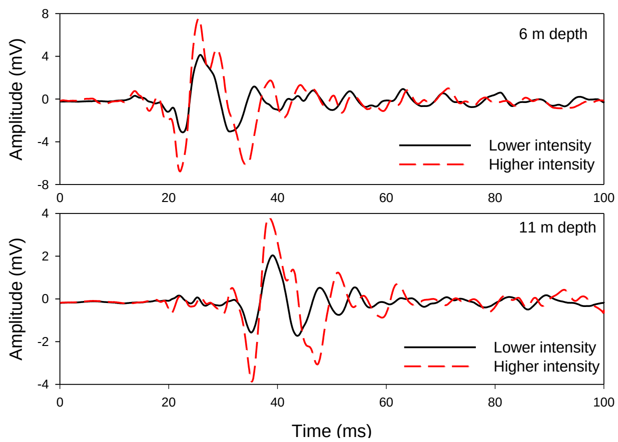

Figure 5. Recorded traces from strokes with greater and lower intensities.

5 SEISMIC SOURCES

5.1 Shear beam size

Two seismic sources, manufactured according to the recommendations of Butcher et al. (2005), were tested. Both were made of wood encased with 25 mm thick steel and with cleats welded to them, to penetrate the ground and prevent them from sliding when struck. One of them is 0.6 x 0.2 m and the other one is 1.15 x 0.20 m (Figures 6 and 7).

Figure 6. Bigger shear beam placed in the rear of the pushing equipment.

Figure 8 shows traces of generated waves by the two seismic sources. The highest energy was generated with the small shear beam. The most important aspect of transmitting energy to the ground is to have the beam as heavily loaded as possible since the shear beam should not move when struck by the sledgehammer. Otherwise the energy would be dissipated and would not travel into the ground (Campanella and Howie, 2008). The stress at the base of each shear beam was calculated resulting 43 kPa for the smaller one and 22 kPa for the larger one. It was noteworthy that the size of the source did not affect the Vs value and good quality signals were obtained with both seismic sources.

Figure 7. Smaller shear beam placed in the rear of the pushing equipment.

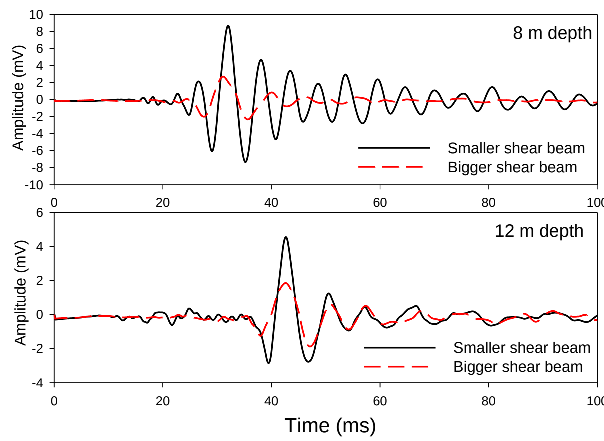

Figure 8. Recorded traces with smaller and bigger shear beams.

5.2 Influence of horizontal offset distance from the cone to the shear beam

The inconvenience of installing the shear beam behind the pushing equipment is that horizontal offset distance (X in Figure 1), from the cone to the centre of the shear beam is 1.80 m, higher than the maximum value recommended by Butcher et al (2005), which is 1.0 m. For longer distances, the seismic waves can refract into a horizontal path resulting in higher velocities (Butcher and Powell, 1996). To meet this recommendation, the seismic source was positioned at the front of the pushing equipment, resulting in a horizontal offset distance of 0.3 m from the cone to the shear beam.

Figure 9 shows the seismic source positioned at the front of the pushing equipment. In several tests, two seismic sources were placed, one at the front and another one at the rear of the pushing equipment. Figure 10 shows the traces obtained with the seismic sources at different positions. It was observed that the amplitude of the waves was similar and both sources generated good quality signals. Figure 11 presents two graphics to compare Vs values with the waves generated simultaneously with the seismic source positioned at the rear of the pushing equipment (X=1.8 m) and at the front (X=0.3 m).

Figure 9. Seismic source placed at the front of the pushing equipment.

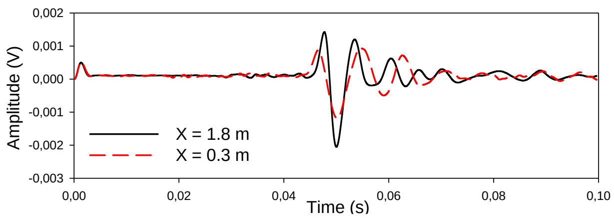

Figure 10. Recorded traces with the shear beam positioned in the front (X=0.3 m) and at the rear (X=1.8 m) of the pushing equipment.

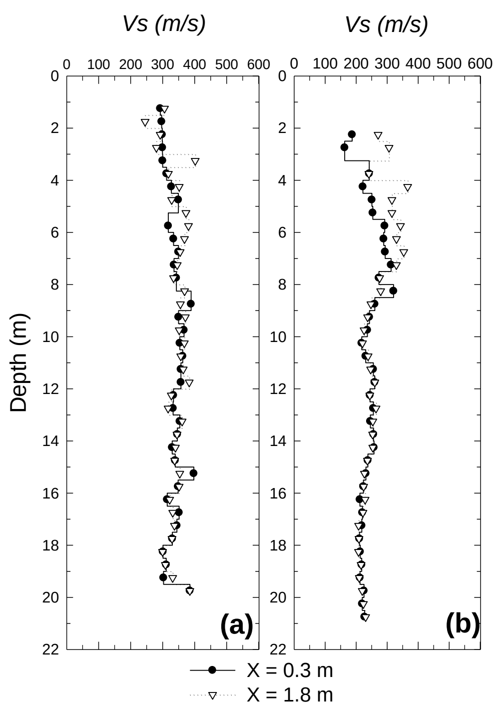

Figure 11. Vs values for seismic source placed at 0.3 m and 1.8 m horizontal offset distances from the cone and the shear beam in tests conducted at the (a) Unesp - Bauru experimental research site and at the (b) Unicamp - Campinas experimental research site.

The analysis of these data showed that in some tests higher shear wave velocities were calculated with X=1.8 m up to about 6 m depth, as described by Butcher and Powell (1996). The Vs profiles obtained with the seismic source positioned at the front (X=0.3 m) were smoother, so this position was considered more appropriate and it was recommended for routine jobs using the developed system. The closer the source, smaller will be the difference between the paths (L_1-L_2) traveled by the waves (equation 1), thus reducing the errors associated with wave propagation in soil mass.

6 DATA INTERPRETATION

6.1 Signal processing

Butcher et al. (2005) recommend recording the signal with no modification. After recording the signal a digital filter was used to remove noise. The digital filter Butterworth low-pass type of third order with cut-off frequency of 400Hz (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 120Hz (Campanella and Stewart, 1992). It allowed a fairly reliable data interpretation. It was observed that the 120Hz low pass filter, suggested by Campanella and Stewart (1992), caused great distortion in the signal. Figure 12 shows the influence of the 400Hz and 120Hz filters in the recorded traces.

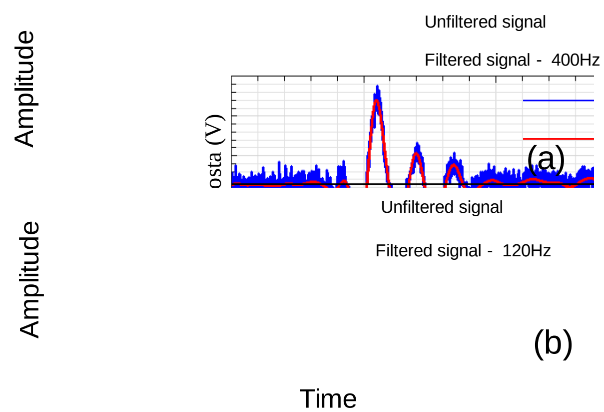

Figure 12. Unfiltered and filtered signals with the Butterworth low-pass digital filter of third order with (a) 400Hz and (b) 120Hz cut-off frequency.

6.2 Interval velocity

6.2.1 True interval vs pseudo interval velocities

The true interval velocity is obtained using two or more transducers positioned at different depths and the time interval is determined as the difference of the wave arrival times in the receivers. Unlike the true interval velocity, pseudo interval velocity is obtained using just one transducer positioned at different depths, successively. The interval velocity is the difference of the wave arrival times to the receiver when placed at two different distances from the source. The shear wave velocity profiles calculated using the true and pseudo interval velocities are presented in Figure 13. The two graphics presented in this figure show three Vs profiles obtained with the pseudo interval, which correspond to each of the geophones installed in the seismic probe, and a Vs profile obtained with the true interval. The interpretation with the pseudo interval velocity is useful because it allows the comparison of the Vs profiles obtained for each geophone.

The results presents in Figure 13 also allows assessing the trigger device performance, since it is known that these two techniques (pseudo and true intervals) provides the same results when an accurate and repeatable trigger device is used (Campanella and Howie, 2008). It can be observed in this figure that the Vs profiles obtained by both techniques were quite similar. In some tests, better results were achieved with the true interval velocity since it eliminates the errors: 1) associated with the trigger device, 2) corresponding to differences of the generated shear waves and 3) caused by inaccuracies in reading depths.

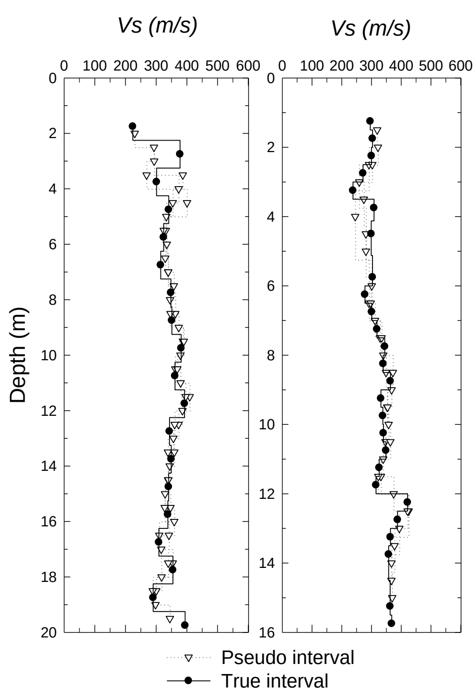

Figure 13. Vs profiles obtained with true and pseudo intervals in tests performed in two experimental research sites from Bauru.

6.2.2 True interval: geophones spaced 1.0 m vs 0.5 m

The way the seismic probe was designed and built allows obtaining two Vs values with the geophones 0.5 m apart and one Vs value with the geophones 1.0 m apart for every single seismic event. It was assumed that the results were 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. The pathway followed by seismic waves (L_1-L_2) would be closer to the spacing of the geophones, reducing errors associated with the wave propagation paths. Figure 14 allows this comparison, which shows that the results were indeed equivalents.

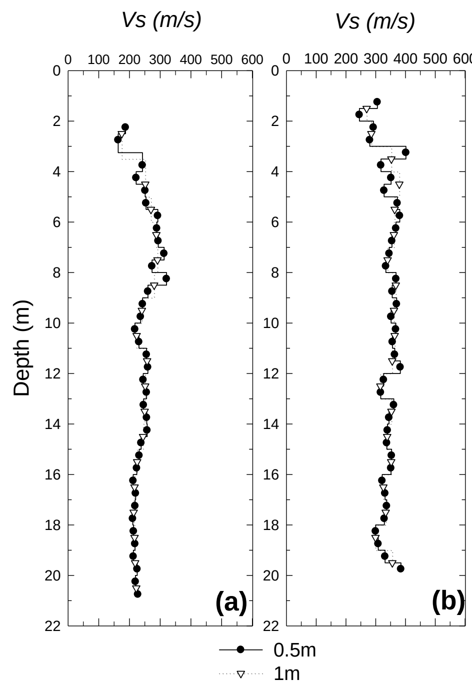

Figure 14. Vs profiles with the geophones 0.5 m and 1.0 m apart in tests conducted at the (a) Unesp - Bauru experimental research site and at the (b) Unicamp - Campinas experimental research site.

6.3 Cross-correlation vs cross-over

Figure 15 shows shear wave velocities calculated by the cross-correlation and cross-over methods. This figure shows that both methods provide equivalent results.

According to Campanella and Stewart (1992) the interpretation by the cross-correlation method is preferable because it considers the whole recorded signal for the time interval determination and not just a point of the signal is used. However, the interpretation with the cross-over method may be preferable if a high acquisition frequency is not available. In tests with sampling rate equal to 10kHz exaggerated repetition of shear wave velocities calculated using the cross-correlation method were observed. The recorded data with the developed system were analyzed using both methods in order to assess the results, before deciding which one would be better for a particular site.

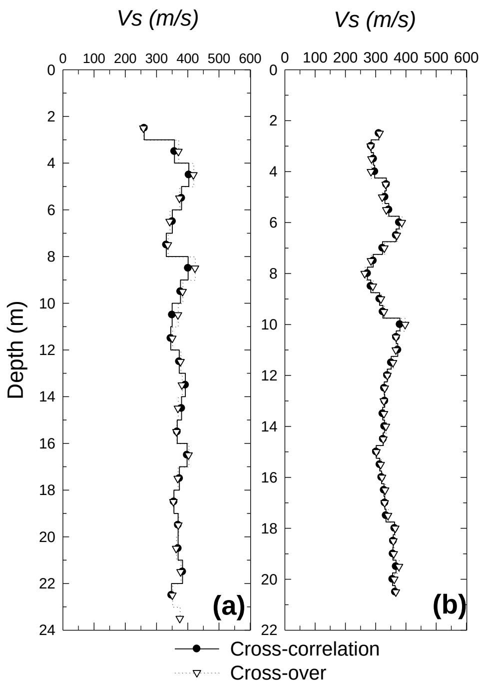

Figure 15. Vs values calculated by cross-correlation and cross-over methods in tests conducted at the (a) Unesp - Bauru experimental research site and at the (b) USP – São Carlos experimental research site.

7 CONCLUSION

The reliability of the down-hole test results is directly related to the quality of the signals, which depends on the equipment and on the precautions to be taken during the test. The most important factor affecting the quality of seismic records was the orientation of the axis of vibration of the geophones. It must remain parallel to the direction of the applied stroke for maximum signal output. The procedure to avoid rotation was to strongly tighten the rods with a pipe wrench, and mark at the top front face of each rod with a felt pen to check for rotation.

Signals with better quality were obtained with lower intensity strokes since excessive vibration of the shear beam by applying stronger strokes caused energy dissipation instead of transferring it to the ground.

The true interval velocity and the cross-correlation method, selecting the main pulse of S waves, were considered the best approaches for data interpretation, although the use of the pseudo interval and the cross-over method have also provided good results. It is interesting to interpret the results by using more than only one technique in order to assess the quality of the data.

Filtering is essential when the noise level is high, as it allows a reliable interpretation of testing data. The low-pass Butterworth filter with a cut-off frequency of 400Hz, which corresponds to the spurious frequency of the used geophones, proved to be quite appropriate, and its use is recommended for this system.

The best results were achieved with the seismic source placed at the front of the pushing equipment, resulting in a horizontal offset distance of 0.3 m from the cone to the centre of the shear beam. The developed system is recommended for routine jobs. The closer the source, the smaller will be the difference between the pathways traveled by the waves, reducing errors associated with wave propagation in the soil mass.

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