White Paper

Seismic CPT: How it works and how it can add value to your GI programme through enhanced data capture

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Introduction

The Seismic Cone Penetration Test (SCPT or SCPTU) is a hybrid ground investigation technique that combines conventional CPT with a measure of seismic wave velocity in the penetrated soil; obtaining data that would otherwise require two separate tests to be carried out. It is a fast and economical method of boosting data output from a CPT led ground investigation (GI) programme and is particularly useful when trying to asses small strain soil moduli such as small strain shear modulus, G_0, and when trying to assess soil properties such as Liquefaction Potential Index (LPI). The basic principle of the test is shown in Figure 1.

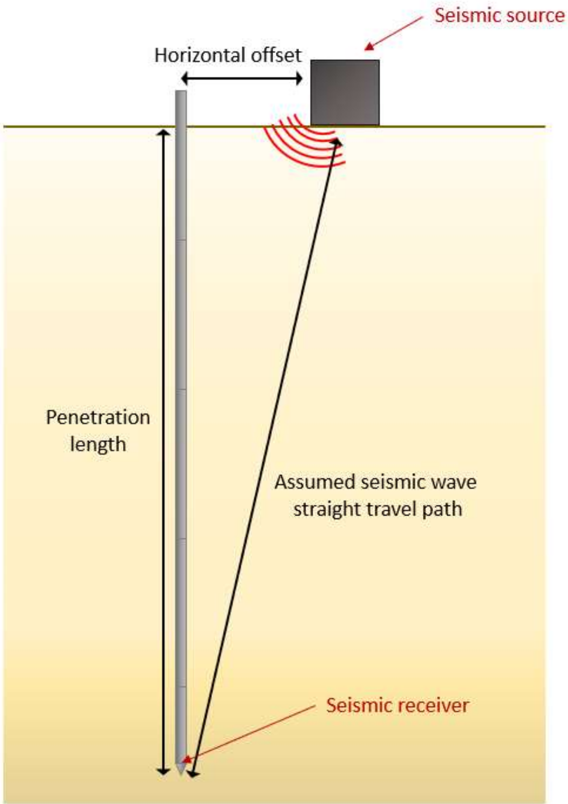

Figure 1. Basic working principle of the SCPT: William Bond, Geomil Equipment

Seismic waves are often categorised as *body waves* and *surface waves*, and for the purpose of SCPT, we are interested in the former. Body waves are split broadly into P and S type which are often referred to as Primary and Secondary because P-waves will arrive before S-waves due to their faster propagation speeds. They are also referred to as Compression (P-waves) and Shear (S-waves) which is more useful because it describes their nature of propagation. In this paper we will refer only to P and S-waves in shorthand and Compression and Shear waves in longhand.

Equipment

For existing users of CPT, additional equipment investment to perform SCPT's is rather minimal. A seismic add-on module is installed behind the CPT cone which consists of an array of receivers, normally accelerometers or geophones, typically in a uni-axial or tri-axial array. In some cases, two seismic modules are used, this is referred to as a dual array setup and as with a single array the receivers can be in a uni-axial or tri-axial arrangement.

Dual array systems provide a true interval rather than a pseudo interval and are therefore preferred when possible. A signal conditioning box is required at surface to separate the seismic data from the standard CPT data and users with analogue setups will require special seismic cables with extra pins for the seismic data.

A waveform generator is required to create the seismic wave for downhole detection. For onshore investigations this typically consists of a striking plate and a hammer, the more sophisticated of which are fully automatic. In near and offshore investigations, a submersible wave generator is required. Often these come in the form of a hydraulic piston which fires at an end plate. Some waveform generators can only produce shear waves (S-waves) however some more advanced are capable of also producing pressure waves (P-waves).

Data Capture

Regardless of the equipment used, the basic method remains the same. The test is started in the same way as a normal CPT. At prescribed intervals, typically every 1m or 0.5m, the advance of the cone is halted, and the waveform is generated. The computer will log the exact moment that the waveform is generated. Once the seismic wave reaches the downhole receivers the waveform is visible on the screen and can be assessed for quality (more on this later). If needed waveforms can be “*stacked*”. Stacking consists of generating multiple waveforms and compiling the data into one waveform. The energy detected due to the seismic wave should have consistent arrivals whereas any background noise and interference should be random allowing the process of data stacking to boost the signal to noise ratio. Typically, the waveforms have an initial peak of a larger amplitude, this is often referred to as the *first arrival*, and subsequent diminishing peaks as the energy produced dissipates.

When generating seismic data for geotechnical analysis the source is designed to generate either P or S-waves depending on how it is operated. When P-waves move through a material, the particles of that material are moving the in the same direction as the wave itself. This is different to S-waves in which the particles move perpendicular to the direction of wave propagation. As the intended direction of wave propagation in a ground investigation is vertically down into the ground, the simplest source, a block or plate struck with a hammer, is struck vertically to generate P-waves and struck laterally to produce S-waves. This is demonstrated in Figure 2.

Of course, the wave generation is rarely perfect and when producing S-waves incidental P-waves will also be produced and a lot of the applied energy will be lost as noise and surface vibration. The best seismic sources are those that can direct as much of the applied energy as possible into the creation of the desired waveform.

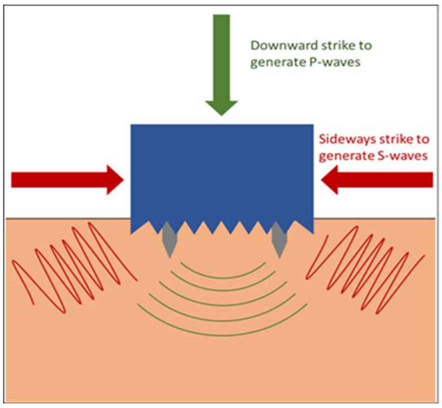

Figure 2. Schematic of a seismic source block: William Bond, Geomil Equipment

When producing S-waves it is typical to create both left and right polarised waveforms, a set of which is shown in Figure 3. This allows for later analysis using the reverse polarity method which is discussed later in this paper.

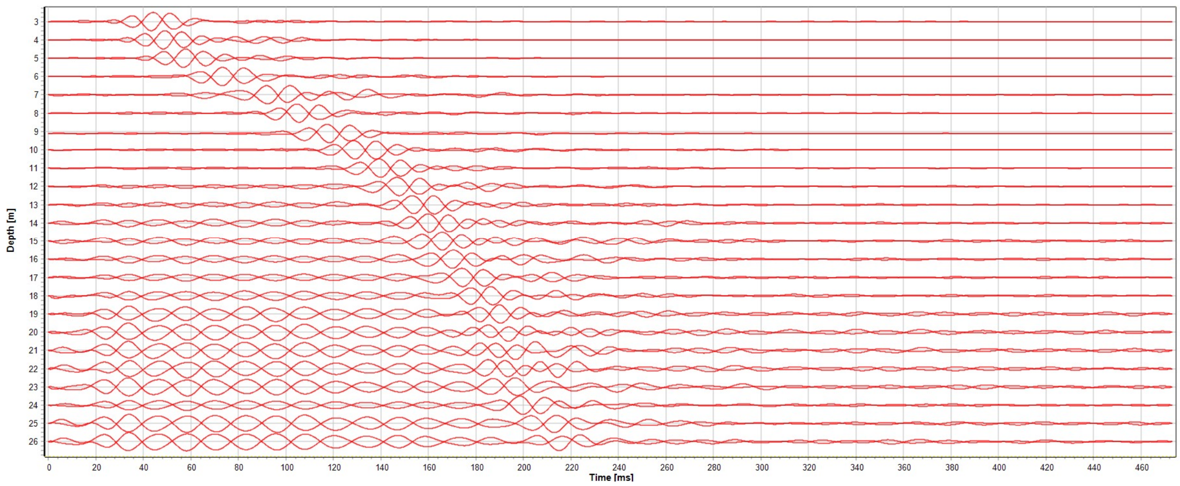

Figure 3. Left and right polarised shear wave, Geomil Equipment data on file

Data Processing and Analysis

Seismic data can require considerable data treatment before analysis. Quality of data and resulting level of treatment is affected by several factors such as background noise during testing and coupling of seismic source to the soil. Initially data is filtered so that only data within a frequency range typical for seismic waves is considered. An unfiltered data set is shown in Figure 4. As seismic tests go deeper and thus the receivers in the cone are further from the signal source, the amplitude of the detected seismic signal lessens. This means that the signal to noise ratio often decreases as test intervals get deeper. Boosting the gain of the receivers is often required at deeper test depths. This increases the sensitivity of the receivers allowing for the detection of the fainter signals. It does, however, also increase the sensitivity to any noise picked up by the receivers.

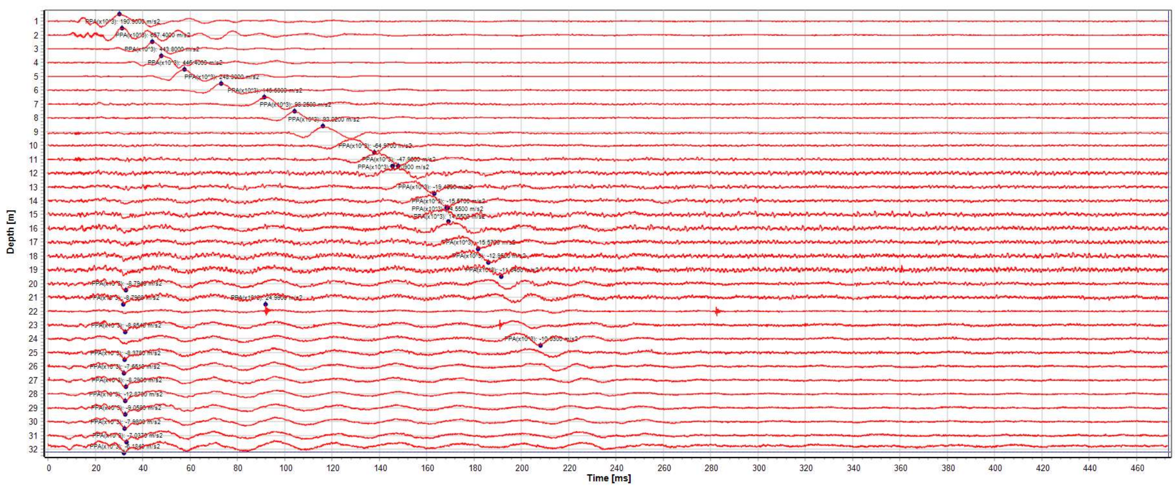

Figure 4. Raw and unfiltered data, Geomil Equipment data on file

As well as stacking the data in the field to boost the signal, data treatment has to be performed afterwards to compensate for diminishing signal strength.

This is often in the form of a process called signal decay which involves removing data either side of the apparent signal, this is illustrated in Figure 5.

This will result in the only high amplitude signal remaining on the seismic waveform being the first wave arrival. This process should be carried out extremely carefully as when carrying out the signal decay you are essentially choosing the peak that will be identified as the first arrival which all further analysis will be based around.

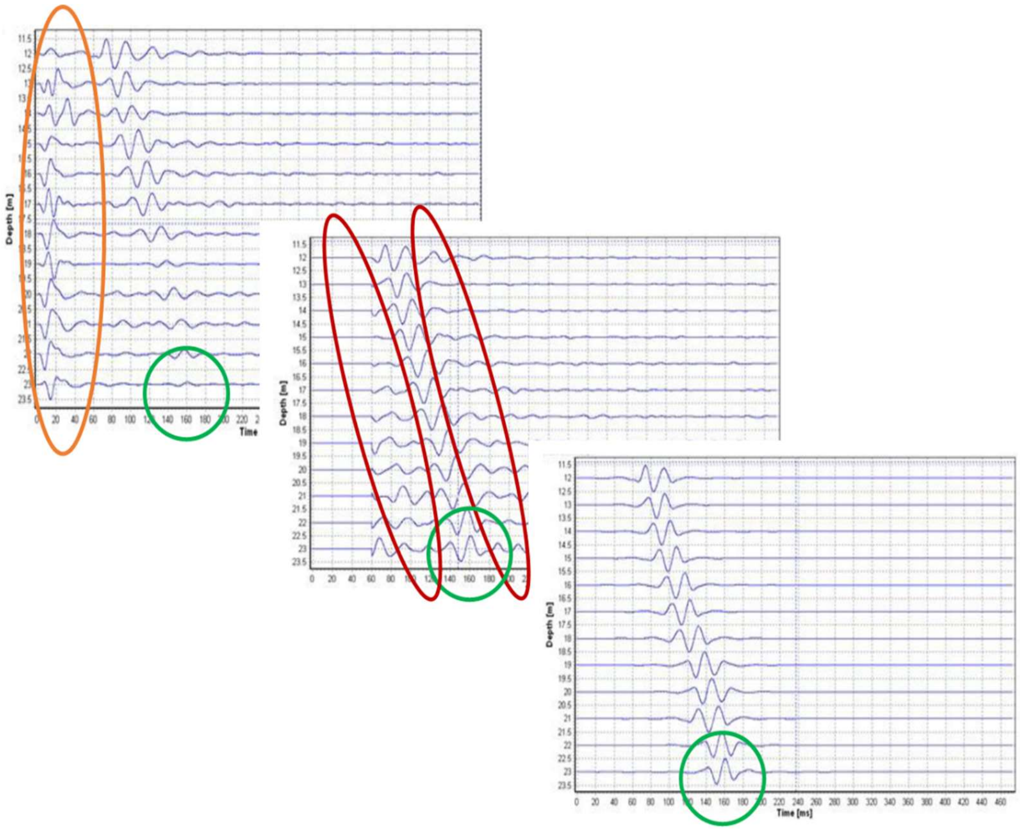

Figure 5. Seismic data as it passes through rounds of cleaning and signal decay: Modified from: BCE SC3-RAV™ 2019 Seismic Data Analysis Software Manual, page 70.

The primary task of the data analysis is to identify the difference in time of wave arrival at subsequent depths. This is normally performed by either the cross-correlation method or reverse polarity method.

The cross-correlation method, illustrated in Figure 6, works by analysing a pair of waveforms and determining the amount of time that would need to be shifted to most closely match the two. The process is typically handled automatically by analysis software. However, if the two waveforms have been smoothed out by an engineer using signal decay leaving only one peak in each waveform then the software will inevitably line up those peaks.

This means that when carrying out the data processing the engineer has great influence on how the data will be interpreted, reinforcing the need for understanding of seismic data and great care when carrying out data processing.

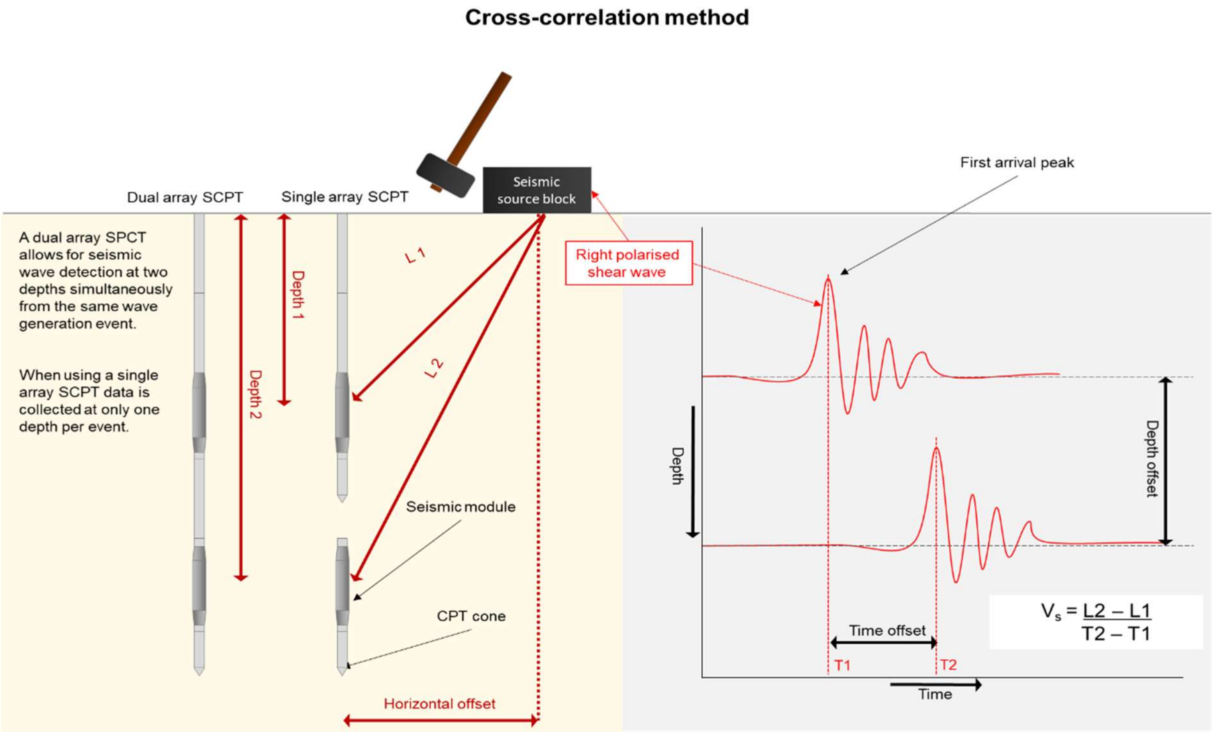

Figure 6. Schematic illustrating the cross-correlation method of data analysis: William Bond, Geomil Equipment.

The reverse polarity method, illustrated in *Figure 7*, requires both left and right polarised shear waves to be created. When viewed superimposed these waveforms will have inverse forms. The engineer then must select the corresponding crossover points of the two waveforms at each depth. Typically, the crossover point directly before or directly after the first arrival peak is chosen. As with the cross-correlation method the resulting value is therefore greatly dependant on the input of the engineer and great care must be taken when performing the data analysis.

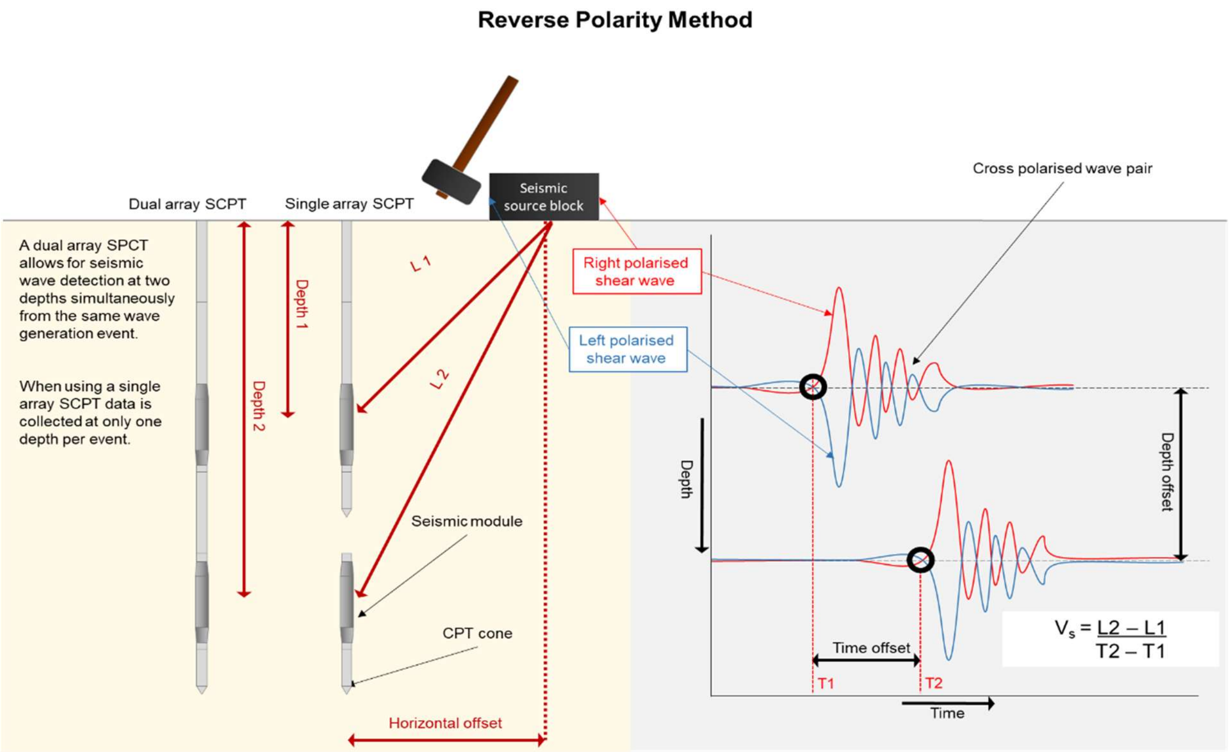

Figure 7. Schematic illustrating the reverse polarity method of data analysis: William Bond, Geomil Equipment

Interpretation and Use of Data

The goal of seismic CPT testing is to accurately measure the velocity of seismic waves through a given interval of soil. Once the speed is determined it can be used to calculate soil parameters. One of the chief uses of this data is using shear wave velocity to calculate small strain shear modulus (G_0). The relationship between shear wave velocity and G_0 is shown below and requires only the input of total mass density of the soil (ρ).

$$G_o = \rho \, V_s^2$$

G_o applies to both static and dynamic soil properties as well as to both drained and undrained soil states and is therefore an incredibly useful soil parameter for geotechnical problems. Research shows that not only is the SCPT an efficient and economical method of obtaining measures of G_0 but that the resulting values are of good reliability (Paul Mayne, 2000).

As well as G_0 small strain Young's modulus (E_0) can be calculated with the below formula:

$$E_o = 2(1 + \upsilon)G_o$$

ν in the formula for E_0 represents Poisson's ratio which can be calculated using the below formula.

$$\nu = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)}$$

However as is apparent from the formula Poisson's ratio requires P-wave as well as S-wave velocity to be calculated. Not only are P-waves velocities faster than S-waves making accurate measurement more difficult, but they are much more greatly affected by the presence of porewater and are therefore hard to measure below the water table.

Of course, an accurate measurement of ρ will further increase the accuracy of the G_0 calculation, as well as any further calculated parameters which derive from G_0 and E_0. Therefore, the most efficient site investigation program, which also leads to the greatest ground model, will likely encompass limited drilling, sampling and testing to obtain a site specific set of soil descriptions as well as a measure of ρ for each material encountered and a widespread SCPT program to efficiently obtain a large data set of accurate measures of shear wave velocity which can be paired with the measured mass density.

Shear wave velocity is also used for assessment of dynamic soil problems such as cyclic loading, affecting soils under wind turbine foundations and highways, and in evaluation of liquefaction potential for soil deposits in potentially seismically active areas as well as in man-made potentially unstable deposits such as tailings dams. Shear wave velocity can be used in the evaluation of Cyclic Resistance Ratio (CRR). Accurate values of CRR can be used to determine if a soil would be expected to liquefy when exposed to a given cyclic stress. There have been many studies into the derivation of such parameters from shear wave velocity and this is a topic of its own. However, for those interested the papers listed in the references are a good place to start.

Conclusions

The SCPT is an excellent hybrid geotechnical tool that combines the soil profiling capabilities of the CPT with an accurate measurement of seismic wave velocities through the penetrated soil profile. It is rapidly deployed and, particularly for existing users of the CPT, is an economical way to boost capabilities for data capture. The data acquired is often used to determine small strain soil moduli such as small strain shear modulus (G_0) and small strain Young's modulus (E_0). The most typical applications for SCPT data are those geotechnical problems associated with dynamic and cyclic soil loading such as wind turbine foundations and highways as well as being very popular for assessment of sensitive man-made deposits such as tailings dams.

Assessing the quality of captured waveforms can be tricky in the field and post processing, if done too heavily, can have a great effect on the resulting velocities. For these reasons great care needs to be taken when capturing and processing seismic data. Engineers presented with data sets for interpretation should be conscientious to study the raw waveforms to verify the resultant velocities.

Dual array systems provide a true interval rather than a pseudo interval eliminating a potential source of error and are therefore often preferred or even prescribed in project specifications.

As with all methods of geotechnical testing it is important to work within the requirements and recommendations of the relevant standards. For seismic CPT there are two relevant standards ISO 19901-8 and ASTM D7400. Furthermore, it is also important to refer to the standards for standard CPT works; ISO 22476-1 and ASTM D5778.

References and Further Reading

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