Abstract

This thesis presents the results of a study of the seismic cone penetration (SCPT) test. The study includes both experimental testing and theoretical analyses of key elements of the SCPT test method, including:

- Characterization of seismic sources;
- Analysis and modelling of impact beams;
- Optimization of shear-wave-signal generation;
- Re-design of *S*-wave sources;
- Methods of calculating and presenting test data;
- Sampling and signal analysis techniques;
- Influence of soil stratification on velocity profiles; and
- Signal randomness and variability.

The modern SCPT test evolved at the University of British Columbia, in Canada, in the 1980's with the modification of the standard cone penetration (CPT) test. This modification introduced velocity transducers to measure shear (*S*) and compressive (*P*) wave velocities. The modified CPT cone performs seismic measurements in addition to the classical parameters of sleeve and tip resistance normally recorded by the CPT test.

The SCPT test generates *S* and *P* waves in the small-strain range of less than 10^{-3} %. This range defines the initial or maximum elastic-deformation range of a material. The measurements obtained with the SCPT test, therefore, correspond to the maximum values of elastic parameters.

At present, the SCPT test uses different execution and interpretation techniques. This is because the test does not yet have a standard protocol for execution. Technical Committee Number 10 (TC 10) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) recently introduced a draft document that provides general guidelines for execution of the test. However, this document does not address important parameters such as interpretation techniques, signal variability and source characteristics.

The present research shows that these parameters play an important role in determining reliability, consistency and accuracy of the SCPT test method. For example, one can use several methods to calculate seismic wave velocities from the test data. Some of these are averaging techniques that generate smooth velocity profiles, while others are more accurate at representing local properties but can produce highly variable results.

This research demonstrates how the pseudo-interval method, for example, is more sensitive to local velocity variations than the assumed-travel-path (ATP) method. The first method can generate abnormal velocity variability when choices of offset distance and test-depth intervals are incompatible with data acquisition (DAQ) properties.

Offset distance has the largest effect on signal variability when it is large relative to the test-depth interval. This can lead to anomalous velocity fluctuations, especially in the upper few meters of testing. This thesis introduces a method to reduce local velocity variability during post-processing analysis, for these cases. The method consists of analyzing signals from shifted-depth intervals, using larger intervals than originally tested, and then overlapping them to match their original test-depth profile.

Accurate sampling and analysis of SCPT test records are crucial in determining *S*-wave velocity (V_s) measurements in the SCPT test method. This is largely because the shear modulus (G_o) relates to bulk density (ρ) of the material and V_s by the relation:

$$G_o = \rho V_s^2$$

A small error in V_s, therefore, results in a relatively large error in G_o.

There are different ways of performing SCPT tests and analyzing test data. This research describes discrete sampling principles and presents analytical methods to obtain first arrival times of generated wave signals. It also introduces easy-to-use design curves to help determine minimum sampling (or re-sampling) rates necessary to reduce error when picking arrival times automatically using a computer program. These include easy-to-use design curves to determine minimum re-sampling rates.

Seismic sources need sufficient coupling with the ground to generate *S*-wave signals. For the generation of *P* waves, which consists of hitting the source in a vertical direction, coupling stress has practically no influence on signal generation. For *S* waves, however, which generate by hitting the beam in a horizontal direction, coupling stress plays an important role in determining the energy of generated signals.

Theoretical analyses performed in this research suggest that energy transfer to the soil during *S*-wave generation increases when the mass of the impact beam decreases in proportion to its hold-down load. These results led to the design of a new seismic source, here referred to as *'de-coupled-load'* source, which maximizes the generation of *S-wave* signals.

This new source uses an innovative system to separate (de-couple) hold--down loads from the impact beam. This reduces the effective mass of the source, which allows more energy transfer to the ground, increases wave energy and improves signal quality. Experimental results presented in this thesis show that the de-coupling mechanism significantly improves performance of *S*-sources. Higher energy S-waves increase signal/noise ratio, which helps improve signal resolution and test depth.

The most common way of applying hold-down loads to beams is to weight these down with the CPT truck. This is a convenient way of loading impact beams but, as suggested in this research, is less efficient than using free weights. One problem with using the CPT truck as load is that it acts as a multi-point source, which contaminates generated signals. In addition, the weight placed on a beam by a CPT truck easily exceeds 10 tons, which far exceeds optimum coupling stresses, as this research shows. Results from SCPT tests performed to 50-m depths using free weights, in combination with de-coupling and optimum loading stresses, confirm these observations.

Structural layering reflects and refracts seismic waves generated by the SCPT test. In the case of reflection, reflected waves always arrive later than either direct or refracted rays. These waves do not play a direct role in the calculation of velocity profiles in the SCPT test. Refracted waves, however, bend toward the SCPT cone and influence velocity values by changes in travel-ray path.

This research evaluates the effect of structural layering on travel-path geometry using simulated SCPT test cases. These cases cover a range of anticipated test scenarios. The results suggest that the influence of refraction on velocity values depends on the contrast in velocity at a given layer interface. The greater the velocity contrast the larger the influence of refraction on calculated velocity is. In general, the results suggest that only small deviations exist, of less than 2%, between actual and assumed direct-travel-path lengths for flat-lying bedding planes.

Dipping, as well as velocity inversion layers, also influence travel-path geometry. For example, an interface dipping to the left of the SCPT cone results in a maximum deviation of 0.2%, while the same geological structure dipping to the right experiences a significantly higher maximum deviation of 2.5%. Finally, the largest deviation calculated for the simulated SCPT tests is for a case with velocity inversion. In this case, the maximum deviation is approximately 4.0%.

Signal repeatability refers to the similarity between repeated signals obtained using identical test-setup conditions. Average and variance are two parameters used in this research to measure similarity and/or variability of signal measurements of amplitude and arrival time. A large variance indicates great variability (or low repeatability) and vice versa. A highly repeatable signal, therefore, is one that possesses a very low variance.

Generating highly repeatable signals is important because it improves measurement accuracy, allows good comparison between tests and increases overall test efficiency, reliability and accuracy. Signal repeatability depends on several factors, including trigger accuracy, DAQ system characteristics, background noise levels, relative position of impact between signals and

type of source used. This thesis presents experimental results obtained on statiscally-large samples to assess signal variability and provides recommendations for improving measurement accuracy.

In particular, research performed both in controlled experiments at the Zwijnaarde university campus site and under normal field conditions at the Deurganckdok in Antwerpen shows that arrival times measured in the SCPT test possess measurable variability that fits a continuous random variable represented by a normal distribution. These results have implications for accuracy of measured arrival times and test reliability. They also underline the importance of selecting a source for the SCPT test that optimizes wave energy and guarantees minimum signal variability.

Finally, this thesis recommends amendments to existing TC 10 guidelines to help standardize the test procedure and improve reliability and accuracy of the SCPT test method. Some of these include requirements for seismic sources. The methods of source characterization used in this thesis offer the possibility to evaluate the performance of seismic sources and to help standardize their performance for the SCPT test.