Seismic cone downhole procedure to measure shear wave velocity - a guideline

Procédé séismique de downhole de cône à la vitesse d'ondes de cisaillement de mesure - une directive

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ABSTRACT

The International Society for Soil Mechanics and Geotechnical Engineering, Technical Committee No 10: Geophysical Testing in Geotechnical Engineering has as part of its brief the task of drafting guidelines for geophysical techniques where no other national or international standards or codes of practice exist. This document is the first of these guidelines and concerns the use of the Seismic Cone to measure downhole seismic wave propagation.

RÉSUMÉ

La Société Internationale de Mécanique des Sols et de la Géotechnique, le Comité technique No. 10 : L'essai géophysique dans la technologie géotechnique a en tant qu'élément de son dossier le charger des directives de rédaction pour des techniques géophysiques où aucune autre norme ou recueil d'instructions nationale ou internationale n'existe. Ce document est le premier de ces directives et concerne l'utilisation du cône séismique de mesurer la propagation séismique d'ondes de downhole.

1 INTRODUCTION

This document is to provide guidance to practitioners and procurers on downhole seismic wave measurement using a seismic cone penetrometer. This guideline is a supplement to the International Reference Test Procedure (IRTP) for the electric Cone Penetration Test (CPT) and the Cone Penetration Test with Pore pressure (CPTU) as produced by the ISSMGE TC16. The document therefore follows and should be used with the CPT IRTP (1999).

The addition of a seismic sensor (usually a geophone but may be an accelerometer or seismometer) inside the barrel of a standard electric CPT is termed a Seismic Cone Penetrometer Test (SCPT) (Robertson et al, 1986). Such a sensor allows the measurement of the arrival of vertically propagating seismic body waves, generated from a source on the ground surface, in addition to the usual cone parameters that are used for detailed stratigraphic logging.

There are two types of seismic body waves, Pressure or Compression waves (P waves) as well as Shear waves (S waves) and seismic sensors react to both. The P wave always arrives first. In soils below the ground water table the P wave typically travels 2 or more times faster than the S wave, so separation of the two body waves is easy. Above the water table, however, the difference is small and separation of P and S waves may be very difficult, requiring specialized techniques. However the most significant difference between P and S waves is that S waves are reversible. Therefore using a source that can produce shear waves of opposite polarity facilitates the identification of S waves.

Since shear waves travel through the skeletal structure of the soil at very small strains, one can apply simple elastic theory to calculate the average elastic small strain shear modulus, over the length interval of measurement, as the mass density times the square of the shear wave velocity. Thus, the shear wave velocity relates directly to stiffness (Massarsch, 2004) and also may be used to estimate liquefaction susceptibility in young uncemented sands (Youd et al, 2001).

2 DEFINITIONS

The following definitions will be used:

Accelerometer: Sensor that produces an output in response to a seismic wave by way of a change in capacitance caused by the relative movement of a mass and the sensor case. An accelerometer detects particle accelerations.

Array: group of devices at one location orientated orthogonally to each other.

Data recording equipment: Equipment to log the signals from the seismometers.

Geophone: Sensor that gives an output in response to seismic waves using the relative movement of a mass (magnet) moving within a coil fixed to the sensor case. A geophone detects particle velocities.

Hammer: Heavy mass to impact the Shear Beam as part of the Source

Interval time: The difference in arrival times of seismic waves at the receivers at two depths/distances from the Source. The 'true interval' is the difference in arrival times between receivers at a fixed distance apart and the 'pseudo interval' is the difference in arrival times to the same receiver when placed at 2 different distances from the source.

Seismometer: Device that produces a calibrated self generated output response to imposed seismic waves and gives maximum output at its natural frequency or fundamental mode (goes into resonance) when activated by seismic waves. A seismometer can be an accelerometer, geophone or a sensor able to detect deflections in the range 0 to 250Hz.

Seismometer natural frequency: Frequency at which the seismometer gives its maximum output and above which the seismometer response is constant.

Shear beam: Beam that forms part of the downhole seismic shear wave Source that is impacted by a Hammer to maximize S waves and minimize P waves.

Source: Device that, when activated, generates polarised shear waves that propagate into the ground. (A basic source will include a loaded Shear Beam, Hammer and a Trigger to activate the data recording equipment).

Trigger: Device attached to either the Shear Beam or the Hammer to initiate the data recording equipment at the instant the Shear Beam is struck by the Hammer.

3 METHODOLOGY

During a pause in cone penetration, a shear wave can be created at the ground surface that will propagate into the ground on a hemi-spherical front and a measurement made of the time taken for the seismic wave to propagate to the seismometer in the cone. By repeating this measurement at another depth, one can determine, from the signal traces, the interval time and so calculate the average shear wave velocity over the depth interval between the seismometers. A repetition of this procedure with cone advancement yields a vertical profile of vertically propagating shear wave velocity. Figure 1 shows 2 alternative schematic arrangements of the SCPT, and Figure 2 shows a typical arrangement of the surface shear wave source.

4 EQUIPMENT

The general arrangement of equipment is shown in Figures 1 and 2.

Seismometer: The seismometer will typically have a natural frequency of less than 28 Hz and must fit inside the cone barrel. The seismometer must be mounted firmly in the cone barrel with the active axis in the horizontal direction and the axis alignment indicated on the outside of cone body. The cone barrel at the location of the seismometer should be of a greater diameter than the sections immediately below the location of the seismometer to ensure good acoustic coupling between the cone barrel and the surrounding soil.

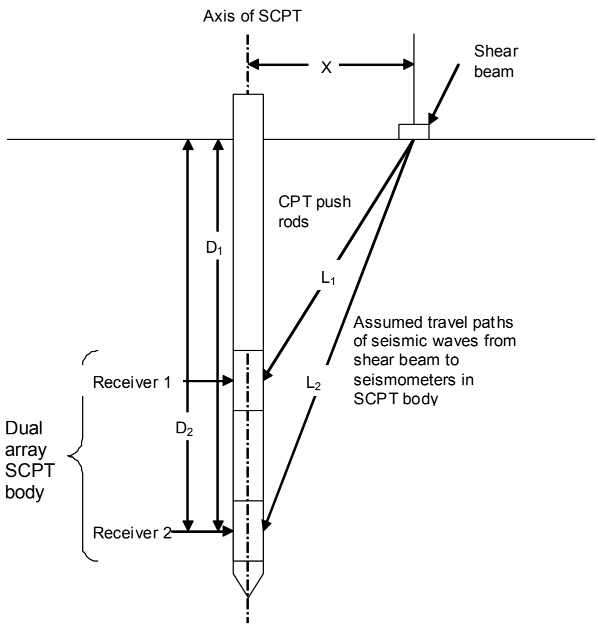

Figure 1b: Schematic diagram of the dual array seismic cone test with required dimensions, D_1, D_2, and X.

Comment: Some seismic cones include 2 seismometers in an array in the horizontal plane set with their active axes orthogonally. This configuration allows compensation for possible rotation of the cone drive rods, (and the cone containing the seismometer) with the subsequent loss in response and also gives orthogonal seismic wave traces from the same source activation. In variable and layered ground conditions, with ambient noise or ground structures that would corrupt the received signals, wave characteristics of the source can be used to identify the shear wave amongst the other waves.

The inclusion of a vertically orientated seismometer will allow the P wave element of the seismic wave to be assessed or P wave arrival measured if a P wave source is used. In many cases the combination of P and S wave data can enhance the

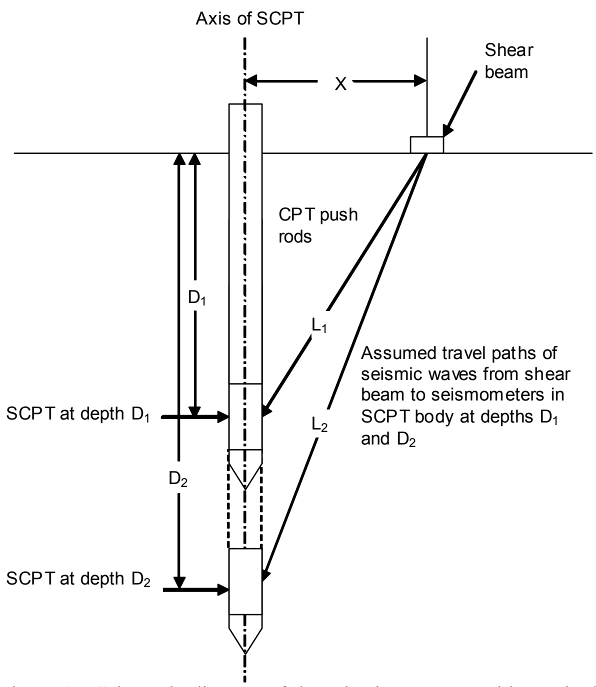

Figure 1a: Schematic diagram of the seismic cone test with required dimensions, D_1, D_2, and X.

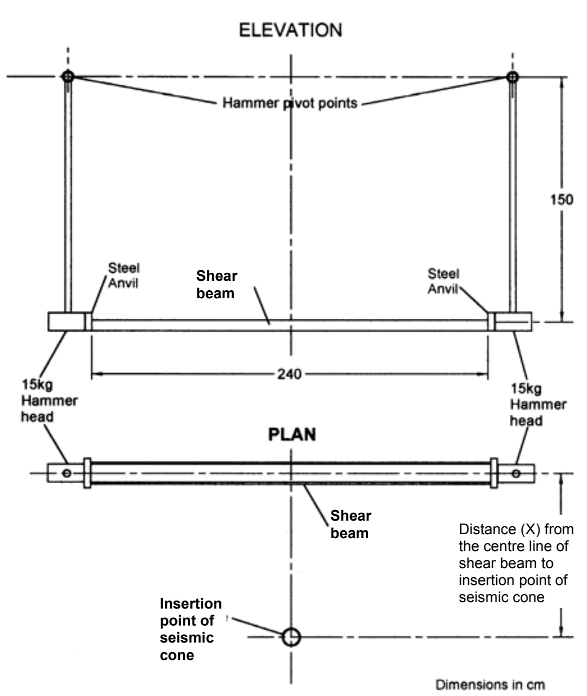

Figure 2: Typical downhole shear wave source setup with shear beam and fixed axis swing hammers.

identification of stratigraphic boundaries.

Shear Beam: The beam can be metal or wood encased at the ends and bottom with minimum 25 mm thick steel. The strike plates or anvils at the ends are welded to the bottom plate and the bottom plate should have cleats welded to it, to penetrate the ground and prevent sliding when struck. The shear beam is placed on the ground and loaded by the levelling jacks of the cone pushing equipment or the axle load from vehicle wheels. The ground should be prepared to give good continuous contact along the whole length of the beam to ensure good acoustic coupling between the beam and the ground. The Shear Beam should not move when struck by the hammers otherwise energy is dissipated and does not travel into ground and does not produce repeatable seismic shear waves. The anvils, on the ends of the Shear Beam, when struck in the direction of the long axis of the Shear Beam, will produce shear waves of opposite polarity.

Comment: The beam can be continuous (approximately 2.4 m long) i.e. greater than the width of a vehicle or equipment used to load the beam and 150 mm wide or alternatively can be two shorter beams placed and loaded so that the anvils oppose and can be struck by the hammers to produce shear waves of opposite polarity. Care must be taken to position the beams and strike direction to maximise S waves and minimise the production of P waves.

Heavy hammer(s): Heavy hammer(s) with head mass of between 5 to 15 kg to strike the plate or anvil on the end of the shear beam in a direction parallel to the long axis of the shear beam and the active axis of seismometer.

Comment: Two fixed axis hammers, one to strike each end of the beam in the specified directions, will significantly speed up the operation and give controllable and consistent source output. A typical setup is shown in Figure 2.

Data recording equipment: The recording equipment can be a digital oscilloscope, a P.C. with installed A/D board and oscilloscope software or a commercial data acquisition system such as a seismograph. The data recording equipment must be able to record at 50 µs (microsecond) per point interval, or faster, to ensure clear uncorrupted signals and to start the logging of the seismometer outputs using an automatic trigger. An analogue anti aliasing filter should be used to avoid corruption of signal frequencies above the device limits. Commercial data recording equipment usually include amplifiers and signal filters to help enhance recorded signals. The effect of these processes on the recorded signals must be considered before their use. For example filtering can cause phase shift of signals and amplification is usually limited to a frequency range. In either case the signals may not be directly comparable.

Comment: Experience has shown that there is a significant advantage to record the unprocessed data and then the effect of filtering and processing can be assessed during post processing. Most modern acquisition equipment allows the viewing of filtered signals during acquisition (to assess quality and repeatability) but saves the data un-filtered. Most modern acquisition equipment allows signal stacking to improve signal to noise ratio.

Trigger: The trigger can be fixed to the hammer head or the beam. The trigger is required to be very fast (less than 10 microsecond reaction time) and repeatable. When the hammer hits the shear beam, the electrical reaction of the trigger activates the trigger circuit that outputs to the signal recording equipment. A typical trigger circuit is given in Campanella & Stewart (1992). A seismic trigger mounted on the beam may be used if it is fast enough, repeatable and delay time is checked and known or a contact trigger that works the instant contact is made between the hammer and the anvil.

Comment: The use of 2 arrays of seismometers set in the cone barrel a fixed distance apart, say 0.5m or 1.0m, (termed a dual array seismic cone, see Figure 1b) would enable the travel time of the shear wave to be measured between the seismometers from the same source activation thereby avoiding possible errors from selection of signal from different source activation, the speed of the trigger, and the accuracy of distance from the source to the receivers from successive pushes of the drive rods to each depth. In this case the seismometers must have identical response characteristics (natural frequency, calibration and damping). However if signals are to be stacked, that is the signals from successive source activations added together to improve signal to noise ratio, the trigger time must be repeatable.

5 TEST PROCEDURES

At the start of the SCPT, the body of the cone should be rotated until the axis of a seismometer is parallel to the long axis of the shear beam.

a) The cone is pushed into the ground, monitoring the inclination of the cone barrel during the push.

Comment: It is important to know the exact location of the receivers in all three axes and the inclinometer in the cone barrel will give the horizontal component and the depth measuring system of the CPT the vertical component.

b) The penetration of the cone is stopped and the depth to the seismometer/s is recorded. The horizontal offset distance, X, from cone to centre of the shear beam should also be recorded (see Figure 1)

Comment: Typically this procedure is carried out at depths greater than about 2-3m in order to minimize the interference of surface wave effects. If the seismic cone includes a fully operative electric cone then it will be advanced at 2 cm/s and stopped typically at a rod break at 1m intervals or for pore water pressure dissipation tests. If acceptable such stoppages can also be used for downhole seismic wave measurements. Alternatively the seismic cone can be pushed to a predetermined depth at which the shear wave velocities are required and the measurements made. To avoid the possible effects of time between stopping, pushing and making measurements it is advisable to keep this time interval consistent. The horizontal distance, X, between the entry point of the seismic cone and the source should be kept at around 1m. Greater distances will require the effects of curved travel paths, that particularly affect single array SCPT's, to be addressed. It is advisable at the first depth of measurement to monitor the output of the receivers without activating the source to determine the ambient seismic noise in the ground and thereby enable the filtering, as far as possible, the ambient noise. Experience has shown that ambient noise can be reduced by retracting the cone pushing system, so that the drive rods are unloaded and there is no contact between the shear beam system and the cone drive rods through the cone drive vehicle, and the cone driving equipment motors are not running.

c) The shear beam is struck by the hammer and the trigger activates the recording equipment that then displays the time based signal trace received by the seismometer.

Comment: For quality assurance, it is recommended to reset the trigger and repeat the procedure until a consistent and reproducible trace is obtained. The voltage-time traces should lie one over the other. If they do not, continue repeating until measured responses are identical. In the case of the dual array SCPT the traces from both the seismometers can be displayed together giving a rapid assessment of the shear wave propagation time. If the seismic wave velocity appears too high then there may be a connection between the cone drive system and the seismic cone so allowing the seismic waves to travel through the cone drive rods instead of the ground.

d) The trigger is reset and the shear beam is then struck by the hammer on the opposite end on the other side of vehicle (causing initial particle motion in the opposite direction and a shear wave of opposite polarity) and procedure in step c) is again completed.

e) Show the traces from step c) and d) together and identify the shear wave (usually clearly seen with traces from the opposite polarity shear waves as a mirror image in time) and pick an arrival time. An example of a pair of signals is shown in Figure 3.

With reversed image traces, the first major cross-over can be taken as the "reference" arrival, or one trace may be used and an arrival pick made visually by an experienced operator. If the wave arrival point is not clear then a significant point that occurs on both traces can be used provided it occurs shortly after the likely wave arrival, later selections are likely to be affected by signal attenuation and dispersion. Alternately, a cross-correlation procedure may be used to find the interval travel time using the wave traces from strikes on the same side at successive depths (Campanella & Stewart, 1992). This technique is more complex, but eliminates the arbitrary visual pick of arrival time and is necessary if symmetry of reverse wave traces is lacking. If a dual array seismic cone is used then the wave traces from each seismometer can be compared to get the travel time between seismometers. Figure 4 shows an example of 'pseudo interval' traces between 4 and 15m depth.

Comment: As depth increases the signal to noise ratio decreases. At large depths it may be necessary to increase signal/noise (depending on the amplification, resolution and accuracy of the data recording equipment). This can be achieved by using multiple source activation events (from 4 to 10) and adding (or stacking) the measured signals, this will reduce most of the random noise and increase signal/noise ratio.

The average downhole shear wave velocity is calculated for the depth interval the cone has been driven between measurements or the fixed distance between the two seismometer sets in a dual array seismic cone.

The average shear wave velocity for the given depth interval in units of m/s and assuming straight ray paths (see Figure 1) is given by Equation (1):

where:

$$V_S = \frac{L_2 - L_1}{T_2 - T_1} \qquad (1)$$

L_2 = calculated length, m of the straight travel path distance from source to receiver at greater depth (use horizontal offset, X, and vertical depth D_2).

L_1 = calculated length, m of the straight travel path distance from source to receiver at shallower depth (use horizontal offset, X, and vertical depth D_1).

T_2 = shear wave travel time from source to receiver at greater depth (along wave path L_2).

T_1 = shear wave travel time from source to receiver at shallower depth (along wave path L_1).

$T_2 - T_1$ = interval travel time.

6 REPORTING OF RESULTS AND INTERPRETATION PROCEDURES

The following information shall be reported:

For each site:

a) Length of shear beam (lengths if two beams are used) and material and composition including anvils.
b) Mass of swing hammers.
c) Fixed or free pivot point of swing hammers
d) Trigger type and location. (for single seismometer seismic cones a typical trigger delay time)
e) Distance (X) of shear beam from insertion point of SCPT, and distance of impact points from the insertion point of the SCPT.

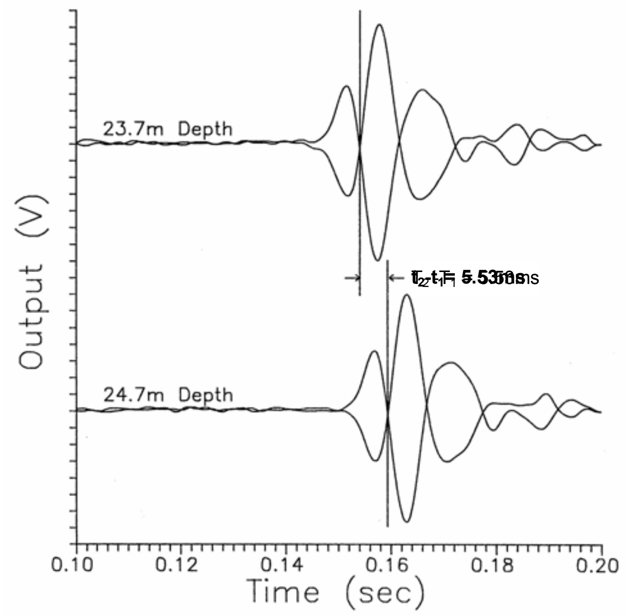

Figure 3: An example of oppositely polarised shear wave traces with clear crossover of traces showing the interval time $T_2 - T_1$.

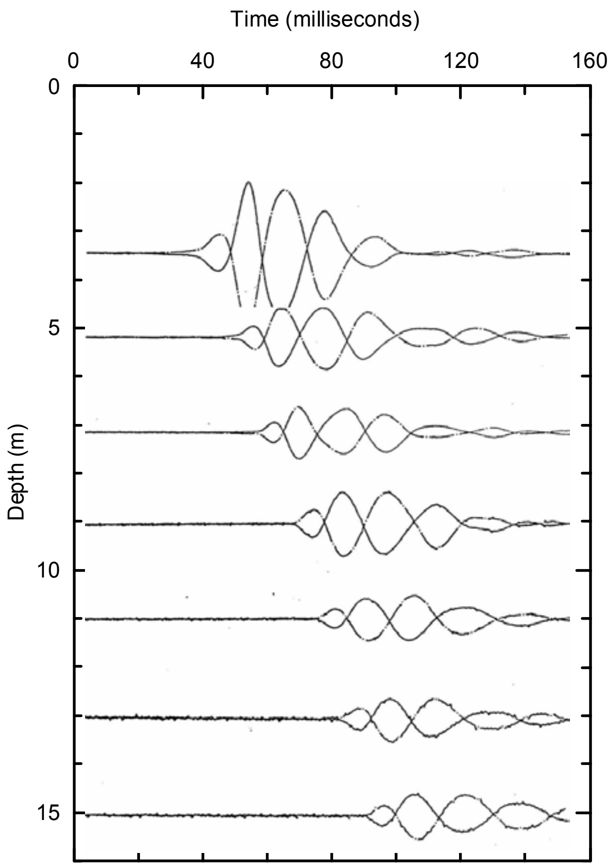

Figure 4: Example of 'pseudo interval' traces of shear waves at depths 4m to 15m.

f) Type of receivers, their specifications, serial numbers and name of manufacturer and last dated response calibration.
g) Type, serial number and specification of data recording equipment and name of manufacturer.

For each location
h) Date and time of test
i) Identification of test
j) Altitude and location of insertion point of SCPT

For each depth:
k) Depth of receiver(s) from ground level.
l) Direction of swing hammer action.
m) Rate of sampling and sample length for each record.
n) Name of files where raw and processed data are recorded including media and location of storage.
o) Type and specification of real time processing included in the recorded data.
p) Type and specification of post measurement processing included in the presented data.
q) Calculated propagation times of the shear waves and the depth range over which the measurement was taken.
r) Calculation of the Shear Wave velocities and the depth range over which the velocity was calculated.

The data files in n) should be stored for future access or for further processing until the end of the project or as specified by the client.

7 ACKNOWLEDGEMENTS

Drafts of this document were discussed at the TC 10 Members Meetings in Prague (2003) and Porto (2004). Valuable comments and suggestions for improvements were made by members of TC 10 as well as members of TC 16 ‘Ground Properties from In-situ Testing’ and TC 1 ‘Offshore and Nearshore Geotechnical Engineering’. Their contributions are acknowledged with gratitude.

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APPENDICES

Appendix A: Maintenance, Checks and Calibrations,

This appendix contains informative guidance on maintenance, checks and calibrations for the SCPT but excludes those parts that are common to the CPT and are included in the CPT IRTP (1999).

A.1: Seismometers.

The seismometers should be checked to ensure they comply to the manufacturers specification in response to seismic waves in regard to frequency, phase and damping before each profile.

Where arrays of seismometers are used, such as for true interval time measurements, each seismometer must have an identical response, in laboratory test conditions, to seismic waves in regard to frequency, phase and damping.

A.2: Source and Triggers

Where single seismometer seismic cones are used the source activation and trigger time delay will have to be quantified. The trigger delay time needs to be repeatable and not vary by more than 1%.