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SEISMIC CONE PENETRATION TEST

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Abstract

A new test, called the seismic cone penetration test (SCPT) is described. A small rugged velocity seismometer has been incorporated into an electronic cone penetrometer. The combination of the seismic downhole method and the CPT logging provide an extremely rapid, reliable and economic means of determining stratigraphic, strength and modulus information in one sounding. Results using the seismic cone penetration test are presented and compared to conventional in-situ seismic techniques.

Introduction

In the last two decades, there has been an increasing interest in soil dynamics, mainly due to the many engineering problems in which the dynamic behaviour of soil is of significance. The increasing interest has resulted in the rapid development of new analytical and dynamic testing methods.

In the field the cross-hole and down-hole methods have become the standard techniques for dynamic testing to determine in-situ shear wave velocity. A polarized shear wave is generated in one borehole (or at the surface) and the time is measured for the shear wave to travel a known distance to the receiving geophone. Elastic theory relates shear modulus, G, soil density, ρ, and shear wave velocity, V_s as follows,

$$G = \rho V_s^2 \qquad (1)$$

Hence, the shear modulus can be determined using in-situ seismic methods for the determination of the shear wave velocity. The shear modulus is largest at low strains and decreases with increasing shear strain (10). The shear strain amplitude in in-situ seismic tests is usually low, of the order of $10^{-4}\%$ or less. Thus, the low strain dynamic shear modulus, G_{max} is usually obtained.

The cost of field cross-hole or down-hole methods is usually high because of the requirement to have one or more boreholes. This has generally made the technique difficult for off-shore use.

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A new test, called the seismic cone penetration test (SCPT), which can dramatically reduce the cost associated with the in-situ determination of shear wave velocity, is described in this paper.

Seismic CPT

The Cone Penetration Test (CPT) is already used extensively off-shore and on-shore for geotechnical investigations. A cone of 10 cm^2 (1.55 in^2) base area with an apex angle of 60° is generally accepted as standard and has been specified in the European and American Standards (ASTM, 1979). A friction sleeve, located above the conical tip, has a standard area of 150 cm^2 (23.2 in^2). A pore pressure transducer has recently been added to measure the dynamic pore pressures during penetration. The cone penetrometer is pushed at the standard rate of 2.0 cm/sec (0.79 in/sec). Standard 1 m (3.28 ft) long rods are used to push the cone penetrometer into the soil. A cable, prethreaded through the center of the hollow push rods, connects the cone to the data acquisition system at ground surface. A small slope sensor is usually incorporated to monitor sounding verticality.

Full details of the design of an electronic cone are given by Campanella and Robertson (3). An example of a modern electronic cone penetrometer which also includes a temperature sensor is shown in Fig. 1. The piezometer-CPT is regarded as the premier test for the continuous logging of soil stratigraphy and shear strength. An example of the extensive data obtained from a piezometer-CPT is shown in Fig. 2. The cone data can be interpreted to give a good continuous prediction of soil type and shear strength (9). Predictions of soil stiffness (modulus) from the cone resistance can be rather poor, especially for overconsolidated soils, with a large potential error. The introduction of seismic measurements into the cone penetration test procedures enables the specific determination of the shear wave velocity and thus the dynamic shear modulus (G_{max}).

To obtain the measurement of shear wave velocity, small rugged velocity seismometers have been incorporated into the cone penetrometer. The miniature seismometer is a Geospace GSC-14-L3 (1.7 cm dia) with a nominal natural frequency of 28 Hz. The seismometer is placed in the horizontal direction and orientated transverse to the signal source to detect the horizontal component of the shear wave arrivals (see Fig. 1). A schematic diagram showing the layout of the standard downhole technique is shown in Fig. 3.

A suitable seismic signal source should preferentially generate large amplitude shear waves with little or no compressional wave component. The shear waves travel through the soil skeleton and are thus related to the soil shear modulus. Results indicate that an excellent downhole seismic shear wave source consists of a rigid beam or platform, steel jacketed and weighted to the ground. It may be struck with a sledge hammer as shown in Fig. 3. If the cone is being pushed by a drill-rig the beam can be weighted down by the rear pads of the drill-rig. If the cone is being pushed by a cone penetration vehicle, the beam can be weighted down by the pads of the vehicle or incorporated into the stabilizing pads for the truck. The beam type

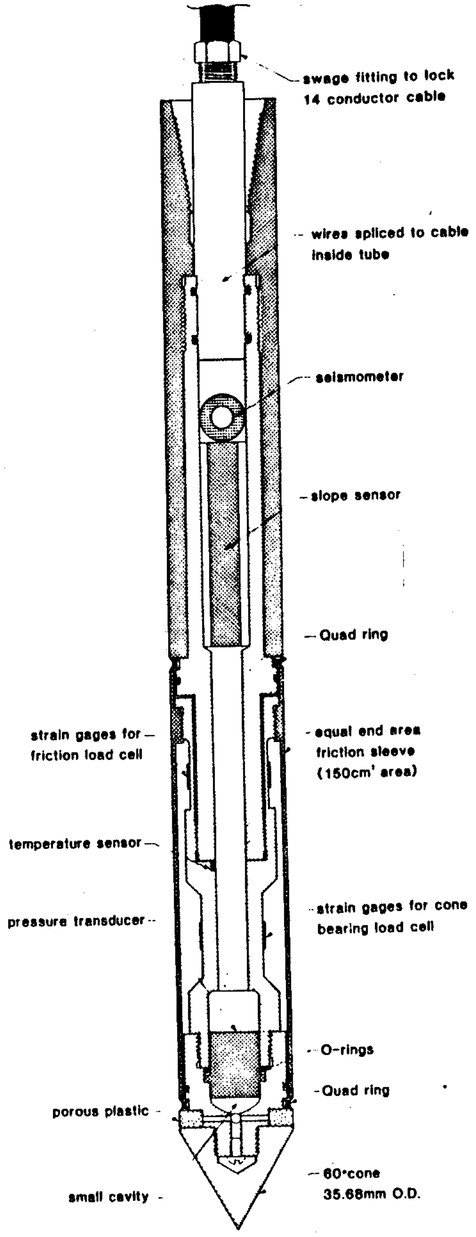


Fig. 1. Seismic Cone Penetrometer.

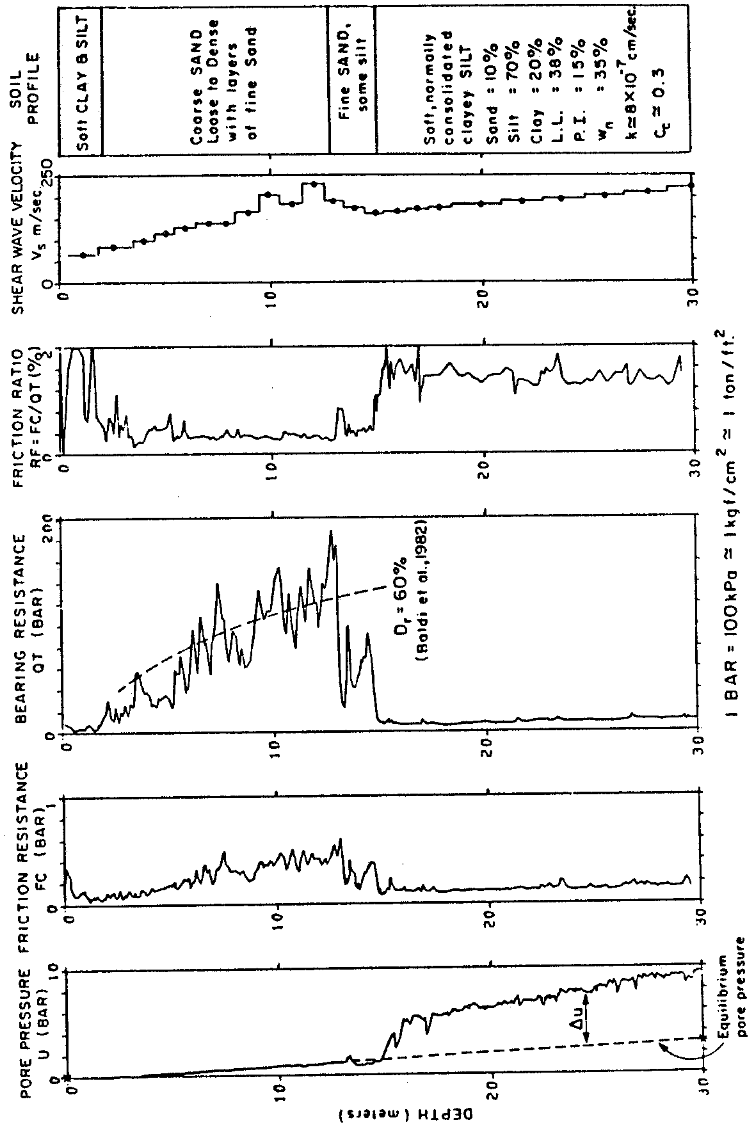


Fig. 2. Soil Profile for Research Site at McDonald's Farm Site (After Campanella et al. 1983).

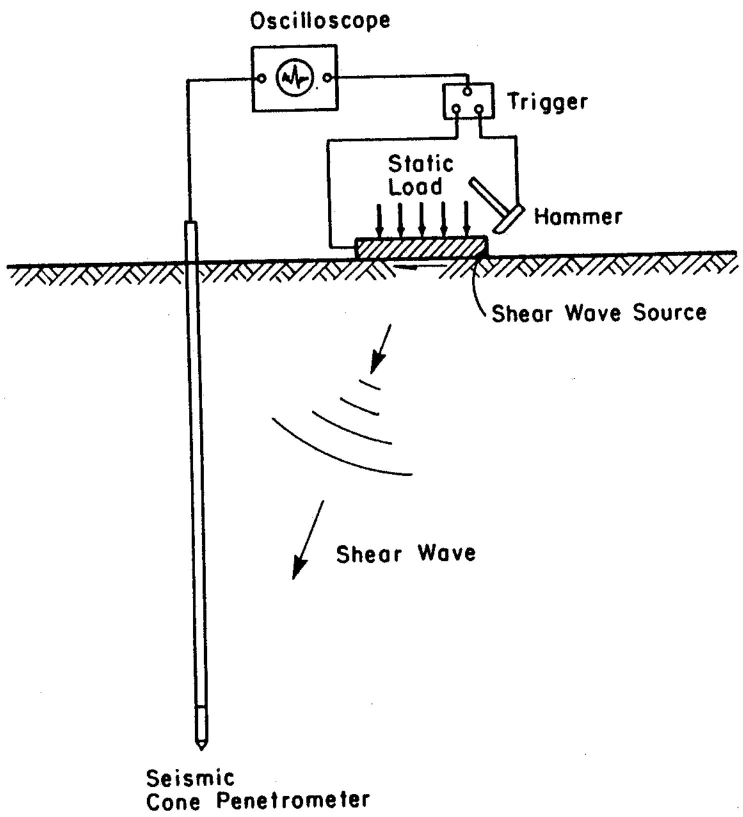


Fig. 3. Schematic Layout of Downhole Seismic Cone Penetration Test.

signal source is usually placed with ends equidistant within about 3 meters (10 ft) of the cone hole. The beam should be securely coupled to the ground so that any energy losses are minimized due to plastic deformation of the soil beneath the beam.

The design and construction of the seismometer carrier provides a snug seating for the seismometer package. The method of advancing the cone penetrometer provides continuous firm mechanical contact between the seismometer carrier and the surrounding soil. This allows excellent signal response. In addition, seismometer orientation can be controlled and accurate depth measurements obtained.

The seismic wave traces detected by the seismometer are recorded on a Nicolet 4094 digital oscilloscope with floppy disk capability. This unit has a 15 bit analog to digital signal resolution, very accurate timing capability and trigger delay capacity. The high resolution oscilloscope is capable of recording clean shear wave traces from forward and reverse single hammer impulses to depths of over 40 metres (131 ft), as shown in Fig. 4. Figure 4 provides a quantitative comparison of the geophone response amplitude and relative shear wave travel times with depth. The geophone output voltage is directly related to the particle oscillation velocity as shown on the inset scales.

The strain level caused by the shear waves can be estimated at any depth during the CPT downhole seismic survey. The relationship between shear strain, γ, shear wave velocity, V_s, and peak oscillation velocity, u, is given by (11),

$$\gamma = \frac{u}{V_s} \qquad (2)$$

Analysis of the existing field data base on plane-wave theory, indicates that the strain amplitudes caused by the hammer-beam source are generally less than approximately $10^{-4}\%$ and appear to decrease with depth.

It has been found that the time for the first cross-over point (shear wave changes sign) is easily identified from the polarized waves (forward and reverse) and provides the most repeatable reference arrival time (8). The arrival time from source to detector is converted vectorially to a vertical travel path. The difference between successive 1 m (3.28 ft) depth measurements of vertical travel path time is used to determine the shear wave travel time over the 1 m (3.28 ft) interval of depth. This technique is called the pseudo time interval method. Because of the short distances and small travel times involved, the oscilloscope must have very high resolution, fast sample times and a very fast, repeatable trigger. The trigger used is similar to that suggested by Hoar and Stokoe (6). The trigger incorporates a MC1455 linear integrated circuit with a rise time of less than 1 μsec. Since the shear wave velocity is squared to calculate G_{max}, a high priority must be given to the accuracy of travel time measurements.

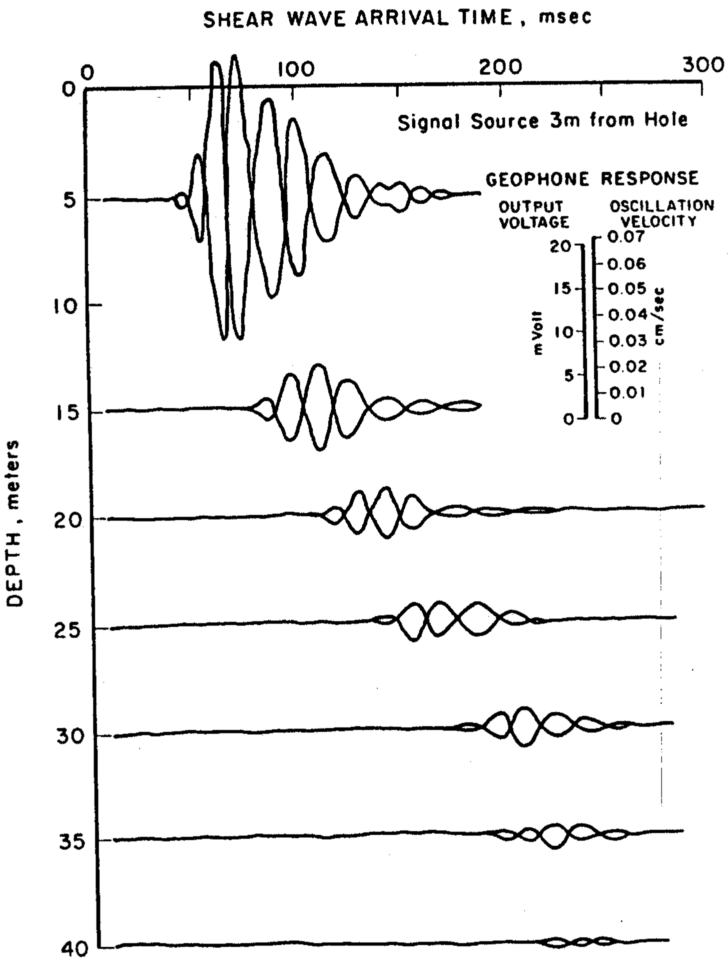
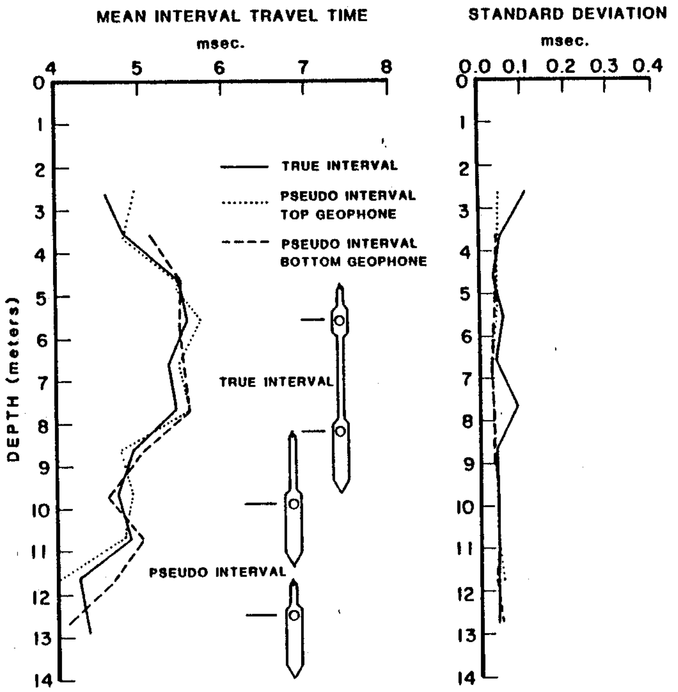


Fig. 4. Quantitative Comparison of Geophone Response Amplitude and Relative Shear Wave Travel Times from Seismic Cone Penetration Test.



True interval:	velocity calculated over the true interval between a pair of geophones.
Pseudo interval:	velocity calculated between successive 1 m (3.28 ft) depth interval using one geophone.

Fig. 5. Comparison of True and Pseudo Interval Travel Times.

To assess the variability of the arrival time measurements and the accuracy and reliability of the trigger system a second geophone system was placed 1 m (3.28 ft.) vertically above the first geophone. This equipment modification allowed the velocity to be calculated over the 'true' interval of 1 m (3.28 ft). This true interval technique could then be compared to the pseudo time interval method described above. The arrival time data was then analyzed assuming a normal statistical distribution at each depth interval. The results from a typical survey with 40 hammer blows using matched geophones is shown on Fig. 5. The data presented in Fig. 5 shows that there is very little error using a single geophone and the pseudo time interval method as compared to the true time interval method with a pair of geophones.

The influence of disturbance caused by the penetration of the cone and rods is thought to be significantly less than that generated by boreholes used in conventional down-hole or cross-hole techniques. The typical size of a borehole is about 100 mm (4 inches) in diameter compared to the cone and rod diameter of 36 mm. Effective stresses are reduced adjacent to boreholes, whereas, effective stresses are increased around the cone. However, the zone of influence of these stress changes are smaller for the cone.

Seismic CPT Results

Downhole seismic shear wave velocity measurements have been made at several sites and in some cases compared to results obtained by others using the conventional crosshole techniques. The seismic cone penetrometer was pushed into the ground at a constant rate of 2 cm/sec (0.79 in/sec). At approximately 1 m (3.28 ft) intervals, the penetration was stopped and shear waves generated at the surface by hitting a beam with a sledge hammer. Generally, only one blow with the hammer was required at each end of the plank to produce a single set of polarized shear waves.

McDonald's Farm Site, Vancouver

A research site for in-situ testing is located on an abandoned farm (McDonald's Farm) near the Vancouver International Airport. Full details of the site are given by Campanella et al. (4). A summary of the soil profile based on sampling and laboratory testing and cone penetration testing is shown in Fig. 2. The interval vertical shear wave velocities calculated from the difference of arrival times are shown in Fig. 6. Note that the results in Fig. 6 indicate that the interval shear wave velocity, and therefore maximum shear modulus, increases with depth. Unfortunately, cross-hole seismic data does not, as yet, exist for this site, however, the maximum shear modulus calculated using the measured shear wave velocities shown in Fig. 6 compare extremely well with G_{max} values estimated from an empirical relationship proposed by Robertson and Campanella (9) for sands using the cone bearing.

Annacis Island, Vancouver

Extensive geotechnical investigations were carried out at the site of the new Annacis Bridge project near Vancouver. The area around the north main pier of the proposed cable stayed bridge consists of Fraser River sands to a depth of about 40 m (131 ft). The water table fluctuates with river level but is nominally about 4 meters (13.1 ft) below ground level.

A summary of the interval shear wave velocities and the cone bearing from the seismic CPT is shown on Fig. 7. The CPT seismic downhole profile was carried out approximately 5 meters (16.4 ft) from a three hole array used for a conventional crosshole seismic survey, which was carried out by others for the B.C. Ministry of Transportation and Highways. The crosshole data was obtained at 2.5 meter (8.2 ft) intervals and is also shown on Fig. 7. The CPT downhole data lies

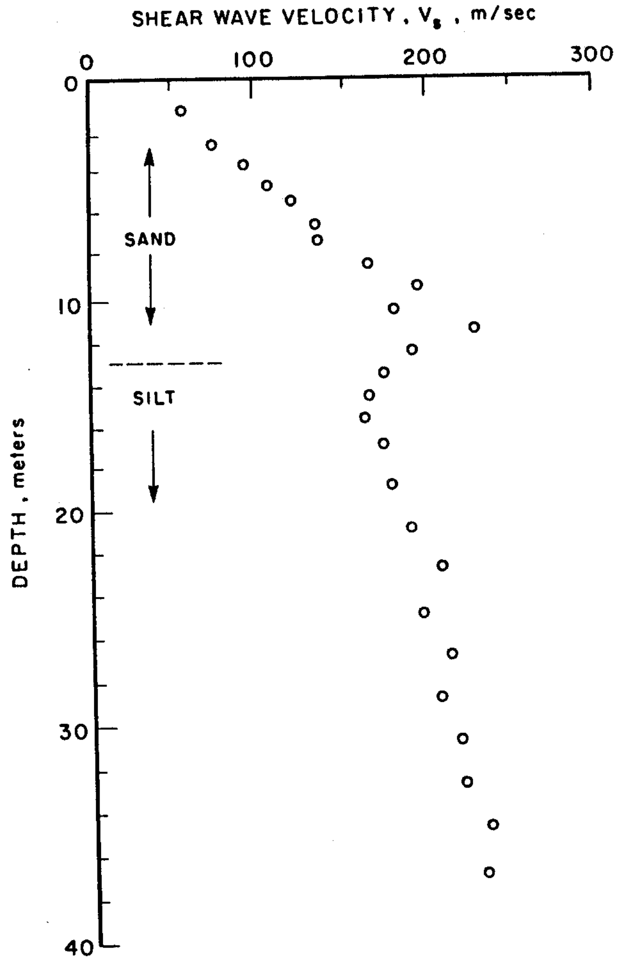


Fig. 6. Calculated Shear Wave Velocity Profile from Seismic CPT at McDonald's Farm Site, Vancouver.

consistently above the crosshole data but generally the two sets of data compare within 20 percent. The seismic CPT data generally follows the trend indicated by the cone bearing profile with little in the way of dramatic velocity changes. The most notable changes occur at 4 m (13 ft) and 11 m (36 ft) where the shear wave velocities increase corresponding to a noticable increase in the cone bearing. The crosshole shear wave velocities, on the other hand, produce more subdued average values.

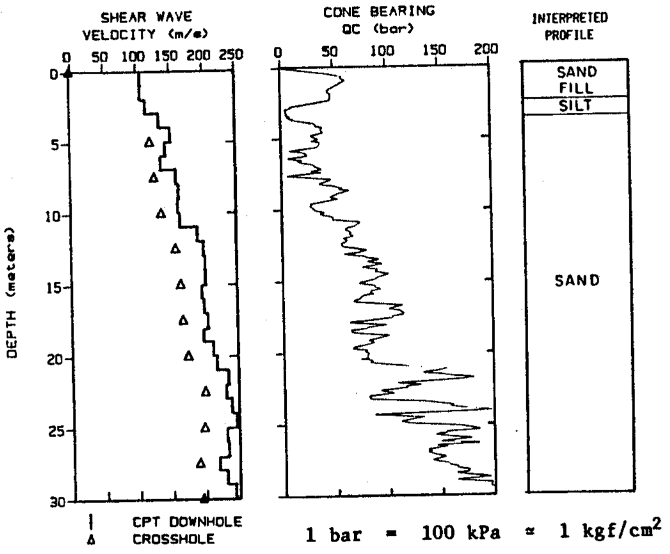


Fig. 7. Comparison of Seismic CPT Downhole and Crosshole Data at Annacis Site, Vancouver.

Imperial Valley, California

In spring 1984 seismic CPT tests were performed at several sites in the Imperial Valley, California with the cooperation of the U.S. Geological Survey and Purdue University. These sites were subjected to recent earthquakes; Imperial Valley, 1979 and Westmoland, 1981. Figure 8 presents the seismic CPT data from the Wildlife site. Full details of the site are given by Bennett et al. (2). The Wildlife site is located next to the Alamo River and exhibited extensive liquefaction during the 1981 earthquake. Also included in Fig. 8 are the shear wave velocities determined by crosshole tests (7). The two seismic profiles compare very favourably with velocities from the two independent methods generally within about 20 percent. Again, it is interesting to note that the shear wave velocities from the seismic CPT respond to variations in the soil profile.

Holmen and Museumsparken Sites, Drammen, Norway

In the fall of 1984 seismic CPT tests were performed at several sites in Norway with the cooperation of the Norwegian Geotechnical Institute (NGI) (5). These sites are well documented sites with extensive field and laboratory data.

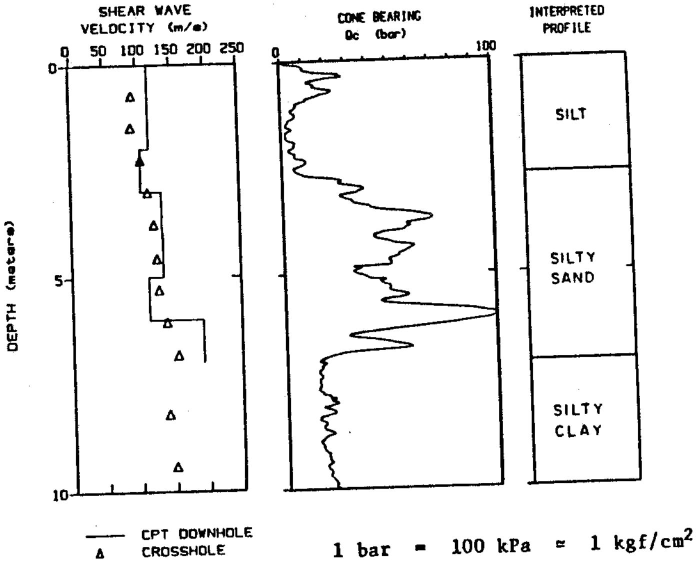


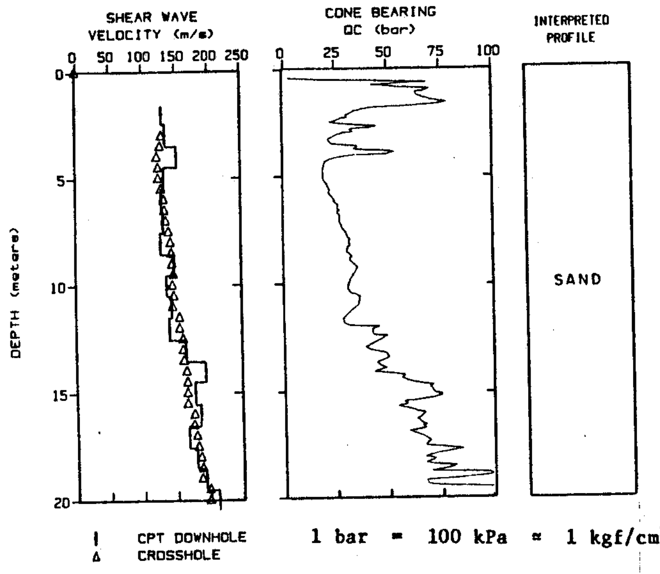
Fig. 8. Comparison of Seismic CPT Downhole and Crosshole Data at Wildlife Site, Imperial Valley.

The Holmen site consists of loose, medium to coarse sand to a depth of 25 m. Figure 9 shows the seismic CPT data compared to the adjacent crosshole data. On average the two seismic shear wave velocity profiles are almost identical at this site showing little, if any, discrepancy between the CPT downhole and conventional cross-hole. The seismic CPT data responds well to variations in the soil profile observed from the cone bearing.

The Museumsparken site consists of the well documented Drammen clay to a depth of 15 m. Figure 10 shows the seismic CPT data compared to adjacent crosshole data. Again the two seismic profiles compare very favourably.

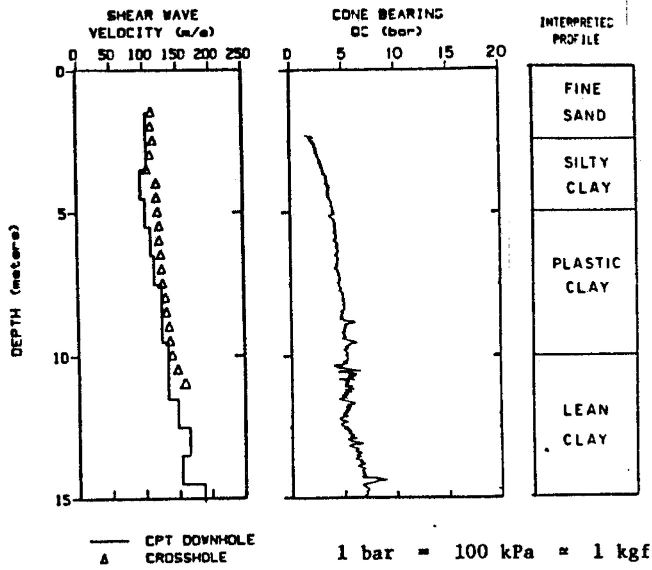
Summary

A new test, called the seismic cone penetration test (SCPT) has been described. The cone bearing, friction sleeve stress and cone pore pressure data can be used to provide a fast and reliable determination of soil type and shear strength. Downhole seismic shear wave velocity measurements can be made during brief pauses in the cone penetration. The shear wave velocity data can be used to provide reliable determination of the maximum dynamic shear modulus. Accurate depth determination is made by measuring the rod length and seismometer orientation is



1 bar = 100 kPa ≈ 1 kgf/cm^2

Fig. 9. Comparison of Seismic CPT Downhole and Crosshole Data at Holmen Site, Norway.



1 bar = 100 kPa ≈ 1 kgf/cm^2

Fig. 10. Comparison of Seismic CPT Downhole and Crosshole Data at Museumsparken Site, Drammen, Norway.

easily maintained throughout the sounding. Hole verticality is monitored throughout the sounding with a small slope sensor installed in the cone. The combination of the seismic downhole method and the CPT logging provide an extremely rapid, reliable and economic means of determining stratigraphic, strength and modulus information in one sounding.

Comparison of the seismic CPT downhole shear wave velocity measurements with those obtained by conventional crosshole techniques show excellent agreement. The seismic CPT is, however, considerably less expensive and a more rapid procedure than the crosshole technique.

The addition of the seismic measurements significantly improves the ability of the cone penetration test to measure soil properties. One area of potential improvement may be in the interpretation of CPT data in cemented or overconsolidated sands and clays. The basic cone data, such as cone bearing and pore pressure, may be used to initially estimate if cementation or overconsolidation exists. The additional shear wave velocity, and thus shear modulus, measurement may then assist in the assessment of cementation or stress history, since cemented or overconsolidated soils can be expected to have significantly higher shear moduli.

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