SEISMIC CPT TO MEASURE IN SITU SHEAR WAVE VELOCITY

By P. K. Robertson,[1] R. G. Campanella,[2] Members, ASCE, D. Gillespie,[3] and A. Rice[4]

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 techniques.

INTRODUCTION

In the last two decades, there has been increasing interest in soil dynamics, mainly due to the many engineering problems in which the dynamic behavior 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 crosshole and downhole methods have become the standard techniques for dynamic testing to determine the in situ shear wave velocity. A polarized shear wave is generated in one borehole (or at the surface) and the time that it takes for the shear wave to travel a known distance to the geophone in the borehole is measured. Elastic theory relates the 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 and of the order of $10^{-4}\%$. Thus, the very low strain level dynamic shear modulus, G_{max} is usually obtained. The cost of such a test is usually high because of the requirement to have one or more boreholes. This has generally made the technique difficult for offshore use.

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.

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[1]NSERC Univ. Research Fellow, Dept. of Civ. Engrg., Univ. of British Columbia, Vancouver, BC V6T 1W5, Canada.

[2]Prof., Dept. of Civ. Engrg., Univ. of British Columbia, Vancouver, BC V6T 1W5, Canada.

[3]Grad. Research Asst., Dept. of Civ. Engrg., Univ. of British Columbia, Vancouver, BC V6T 1W5, Canada.

[4]Engr., Golder Associates, Vancouver, BC V5Y 1N5, Canada.

Note.—Discussion open until January 1, 1987. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 20, 1985. This paper is part of the *Journal of Geotechnical Engineering*, Vol. 112, No. 8, August, 1986. ©ASCE, ISSN 0733-9410/86/0008-0791/$01.00. Paper No. 20848.

Robertson et al., 1986 "Seismic CPT to measure in-situ shear wave velocity"
ASCE J. GED, 112(8), 791-803

Seismic CPT

The cone penetration test (CPT) is already used extensively offshore and onshore for geotechnical investigations. A cone of 10 cm^2 (1.55 sq in.) 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 sq in.). 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/s (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

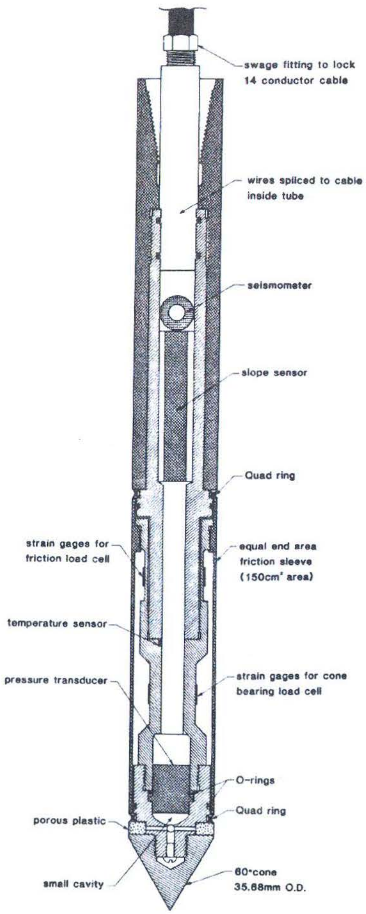


FIG. 1.—Seismic Cone Penetrometer

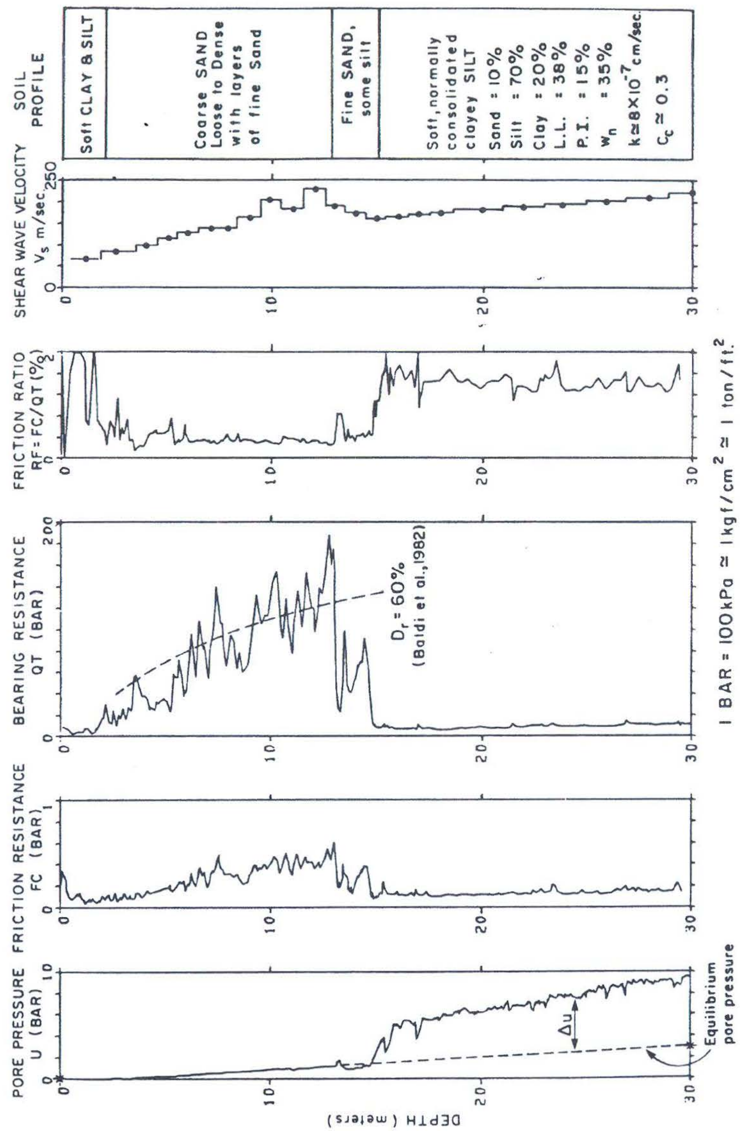


FIG. 2.—Soil Profile for Research Site at McDonald's Farm Site (after Campanella, et al., 1983)

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 that 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 dynamic shear modulus (G_{max}).

To obtain the measurement of dynamic shear modulus, a small rugged velocity seismometer has been incorporated into the cone penetrometer. The miniature seismometer is a Geospace GSC-14-L3 (1.7-cm diameter) 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 signal source is usually placed with ends equidistant within about 3 m (10 ft) of the cone hole. The beam should be securely placed on 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 slope sensor within the cone measures the slope of the cone. Experience using CPT suggests that once a cone tip is deflected, it continues along a path with a relatively consistent radius of curvature. Slope sensors within modern electronic cones can register changes in slope of the cone tip of less than 0.5°. Thus, the error in V_s due to a nonvertical propagation path can be restricted to less than 1% for most penetration depths of less than 30 m.

The seismic wave traces detected by the seismometer are recorded on a Nicolet 4094 digital oscilloscope with floppy disk capability. This unit

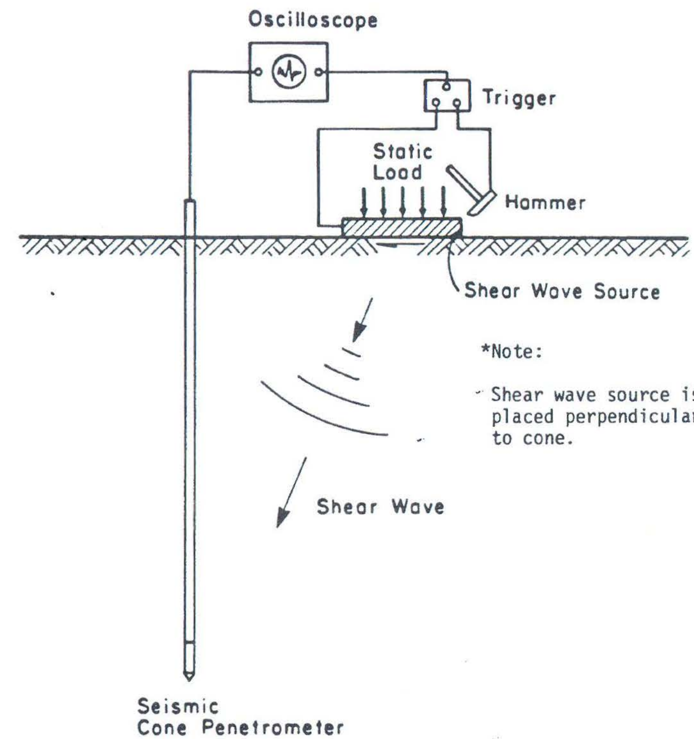


FIG. 3.—Schematic Layout of Downhole Seismic Cone Penetration Test

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 m (131 ft), as shown in Fig. 4. Fig. 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, based on plane-wave theory, indicates that the strain amplitudes caused by the hammer-beam source are generally less than 10^{-4}% and decrease with depth.

It has been found that the time for the first crossover point (shear

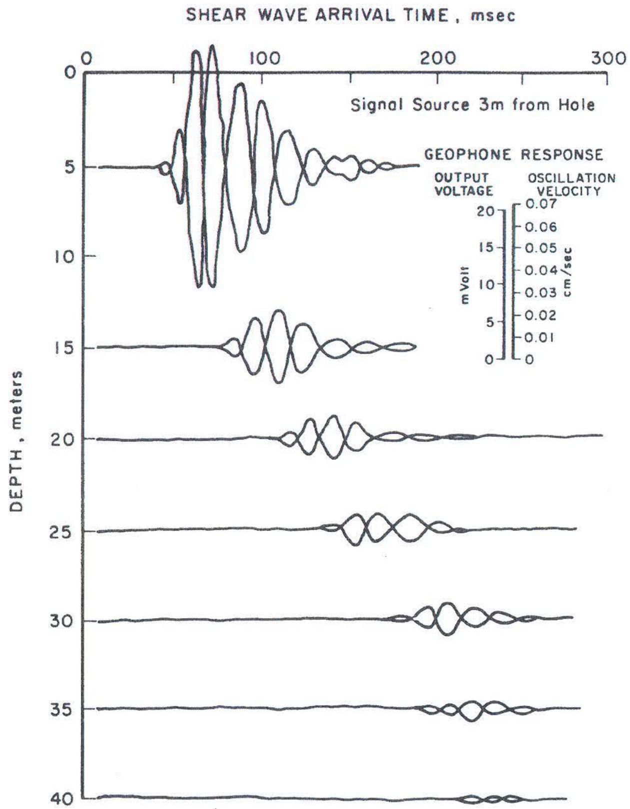
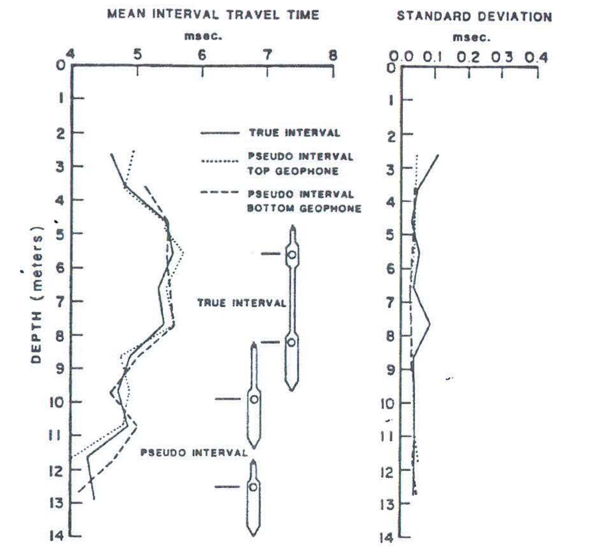


FIG. 4.—Quantitative Comparison of Geophone Response Amplitude and Relative Shear Wave Travel Times from Seismic Cone Penetration Test

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.

To assess the variability of the arrival time measurements and the accuracy and reliability of the trigger system, a second geophone system



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

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 (3.25 ft). This true interval technique could then be compared to the pseudo time interval method previously described. 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 in Fig. 5. The data presented in Fig. 5 show that there is a maximum 10% error in the calculation of shear wave velocity using a single geophone and the pseudo time interval method as compared to the true time interval method with a pair of geophones.

A 10% error in V_s represents an error of about 20% in G_{max}. However, the comparison between the true and pseudo methods shown in Fig. 5 show that the error in V_s is generally less than 10%.

Seismic CPT Results.—Downhole seismic shear wave velocity measurements have been made at several sites and in some cases were 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/s (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 the maximum shear modulus, increases with depth. Unfortunately, crosshole 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 compared well with G_{max} values estimated from empirical relationships 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

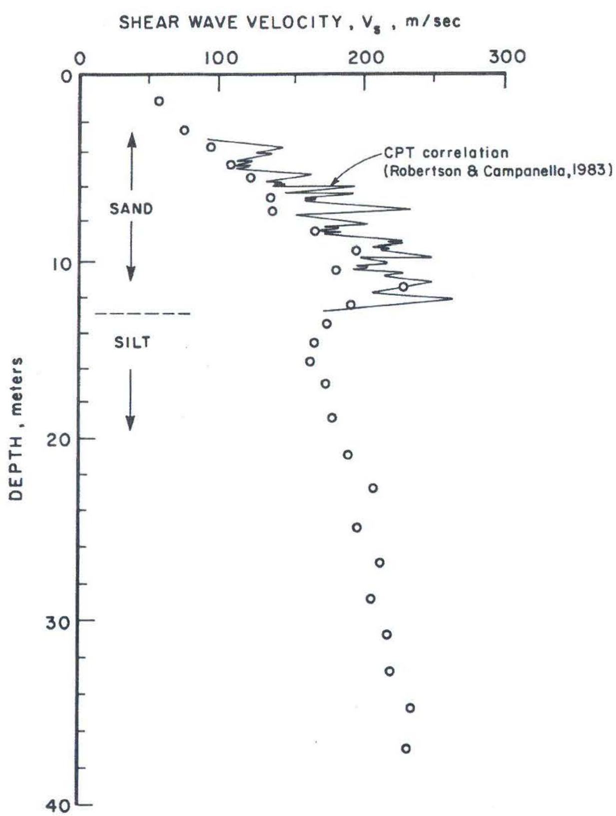


FIG. 6.—Calculated Shear Wave Velocity Profile from Seismic CPT at McDonald's Farm Site, Vancouver

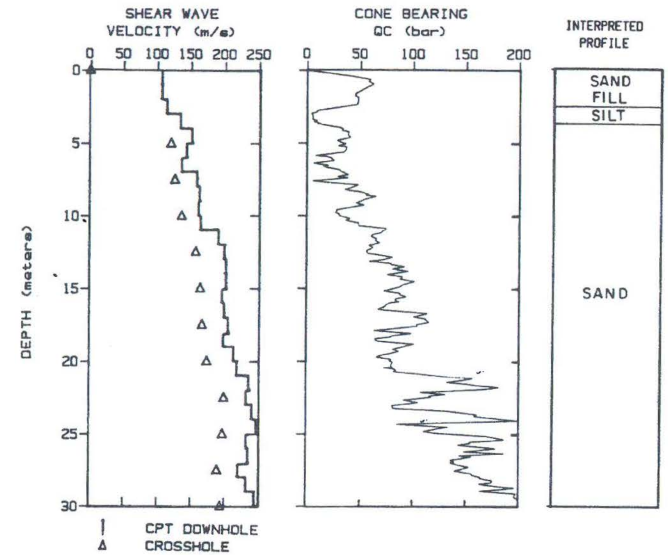


FIG. 7.—Comparison of Seismic CPT Downhole and Crosshole Data at Annacis Site, Vancouver

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 m (13.1 ft) below ground level.

A summary of the interval shear wave velocities and the cone bearing from the seismic CPT is shown in Fig. 7. The CPT seismic downhole profile was carried out approximately 5 m (16.4 ft) from a three-hole array used for a conventional crosshole seismic survey, which was carried out by others for the British Columbia Ministry of Transportation and Highways. The crosshole data was obtained at 2.5-m (8.2-ft) intervals and is shown on Fig. 7. The CPT downhole data lies consistently above the crosshole data but generally the two sets of data compare within 20%. The seismic CPT data generally follow 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 noticeable increase in the cone bearing. A difference in V_s of 20% represents a difference of about 40% in G_{max} measured using the CPT downhole and conventional crosshole. This may be due to anisotropic conditions, which could affect wave propagation.

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 in 1979 and Westmoland in 1981. Fig. 8

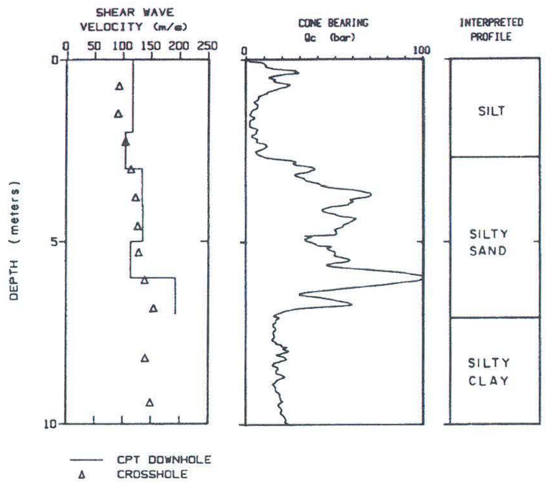


FIG. 8.—Comparison of Seismic CPT Downhole and Crosshole Data at Wildlife Site, Imperial Valley

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 favorably with velocities from the two independent methods generally within about

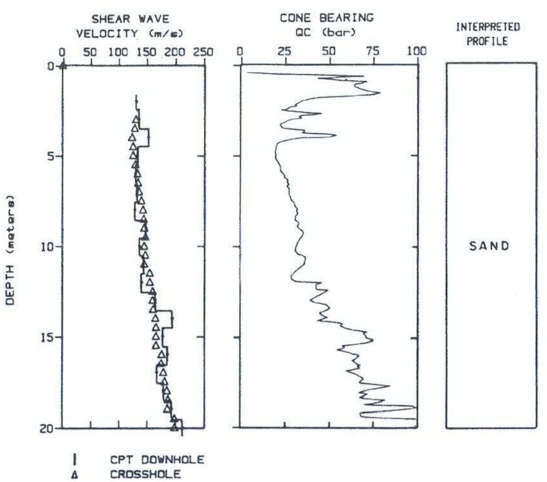


FIG. 9.—Comparison of Seismic CPT Downhole and Crosshole Data at Holmen Site, Norway

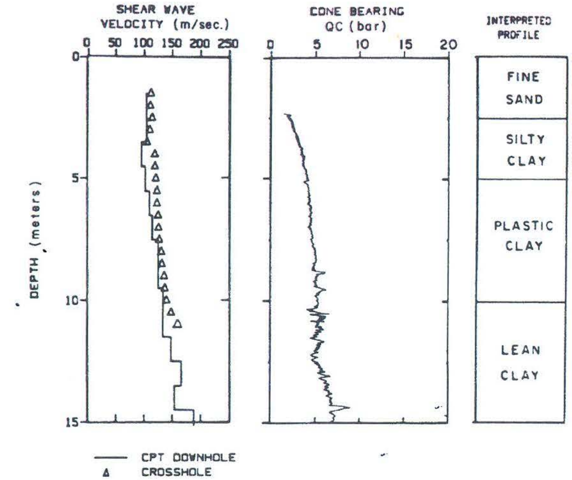


FIG. 10.—Comparison of Seismic CPT Downhole and Crosshole Data at Museumsparken Site, Drammen, Norway

20%. Again, it is interesting to note that the shear wave velocities from the seismic CPT respond well to small 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.

The Holmen site consists of loose, medium-to-coarse sand to a depth of 25 m. Fig. 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 crosshole. 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. Fig. 10 shows the seismic CPT data compared to adjacent crosshole data. Again the two seismic profiles compare very favorably.

Summary

A new test, called the seismic cone penetration test 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 determine the maximum dynamic shear modulus. Accurate depth determination is made by measuring the rod length, and seismometer orientation is 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 provides 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 good agreement. The seismic CPT is, however, considerably less expensive, and a more rapid procedure than the crosshole technique, especially if CPT procedures are employed as part of the standard site investigation.

The seismic CPT measures the shear wave velocity of a vertically propagating shear wave. Anisotropic conditions may produce a difference of shear wave velocity calculated using the seismic CPT downhole method and the crosshole methods.

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.

Acknowledgments

Research on the seismic cone was initiated in 1980 as a result of support and discussions with Fugro, Inc., Long Beach, currently Ertec, Inc.

The assistance of the Natural Sciences and Engineering Research Council; the British Columbia Ministry of Highways and Transportation; Golder Associates, Vancouver; T. Lunne and T. Eidsmoen of the Norwegian Geotechnical Institute; L. Youd of the U.S. Geological Survey; J. L. Chameau of Purdue University; and the technical staff of the Civil Engineering Department, University of British Columbia is appreciated. The work of N. Laing and J. Greig is also appreciated.

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