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A SEISMIC CONE PENETROMETER FOR OFFSHORE APPLICATIONS

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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 onshore in-situ techniques. Results are also presented from seismic cone testing performed offshore in the shallow Canadian Beaufort Sea.

Introduction

In the offshore environment, the dynamic behaviour of soil can be of great importance. Rapid development has taken place in the last decade on new analytical and dynamic testing techniques.

For onshore investigations, the cross-hole and down-hole 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 is measured for the shear wave to travel a known distance to the geophone in the borehole. Elastic theory relates the shear modulus, G, soil density, ρ, and shear wave velocity, V_s as follows,

$$G = \rho V_s^2 \tag{1}$$

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 (Seed and Idris, 1970). 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 or impossible for off- shore 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, will be described in this paper.

Seismic CPT

The Cone Penetration Test (CPT) is already used extensively offshore for geotechnical investigations. A cone of 10 cm^2 base area with an apex angle of 60° is generally accepted as standard and has been specified in the European and American Standards. A friction sleeve, located above the conical tip, has a standard area of 150 cm^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. 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 (1981) and Schaap and Zuidberg (1982). 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. 1. The cone data can be interpreted to give a good continuous prediction of soil type and shear strength (Robertson and Campanella, 1983). 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}). Thus, the combined measurement of soil strength and modulus provides a means to identify the complete stress-strain relationship of soil units which is required for many complex finite element analyses.

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 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. A schematic diagram showing the layout of the standard downhole technique is shown in Fig. 2.

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 onshore downhole seismic shear wave source consists of a

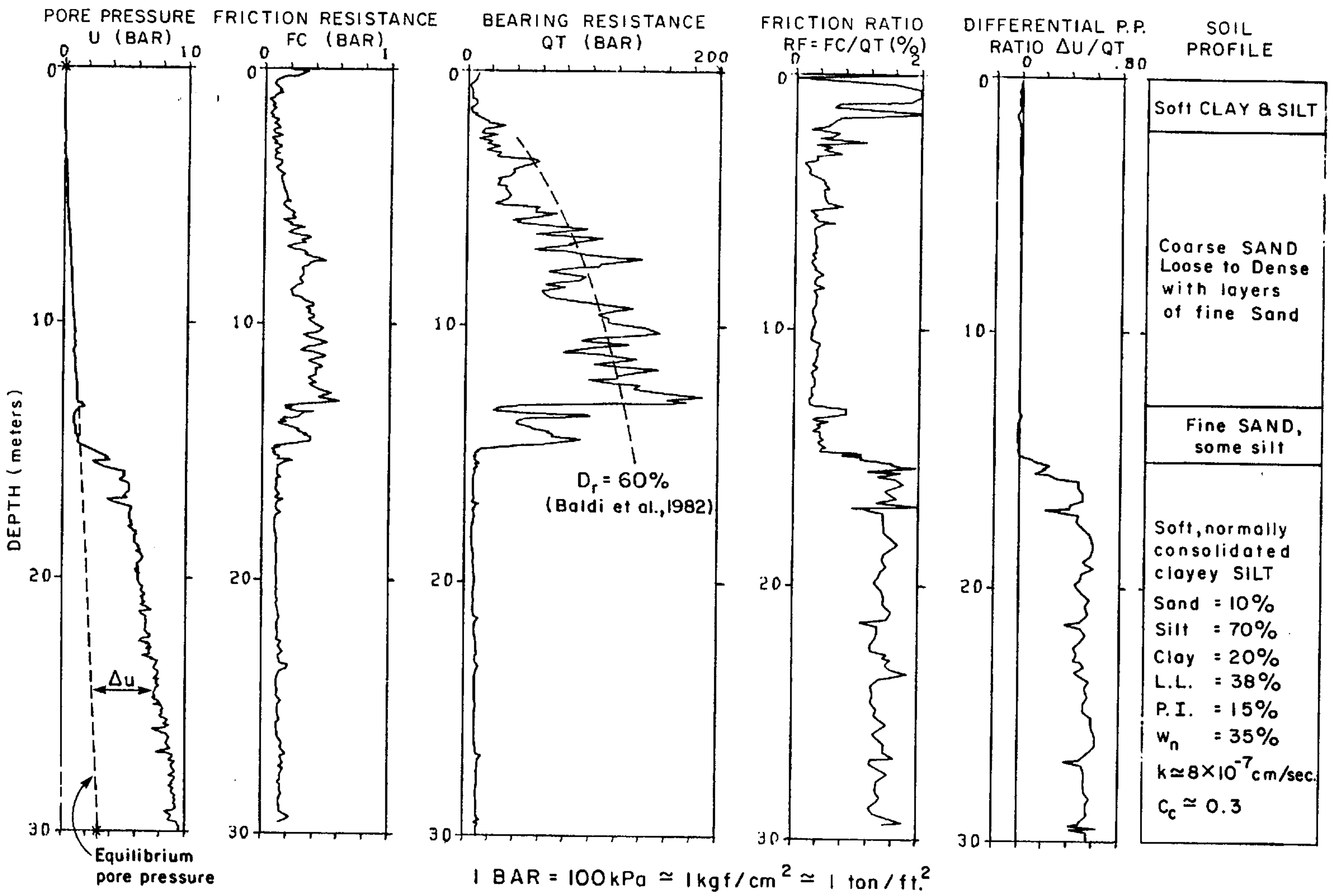

Fig. 1. Soil Profile for Research Site at McDonald's Farm Site (After Campanella et al. 1983).

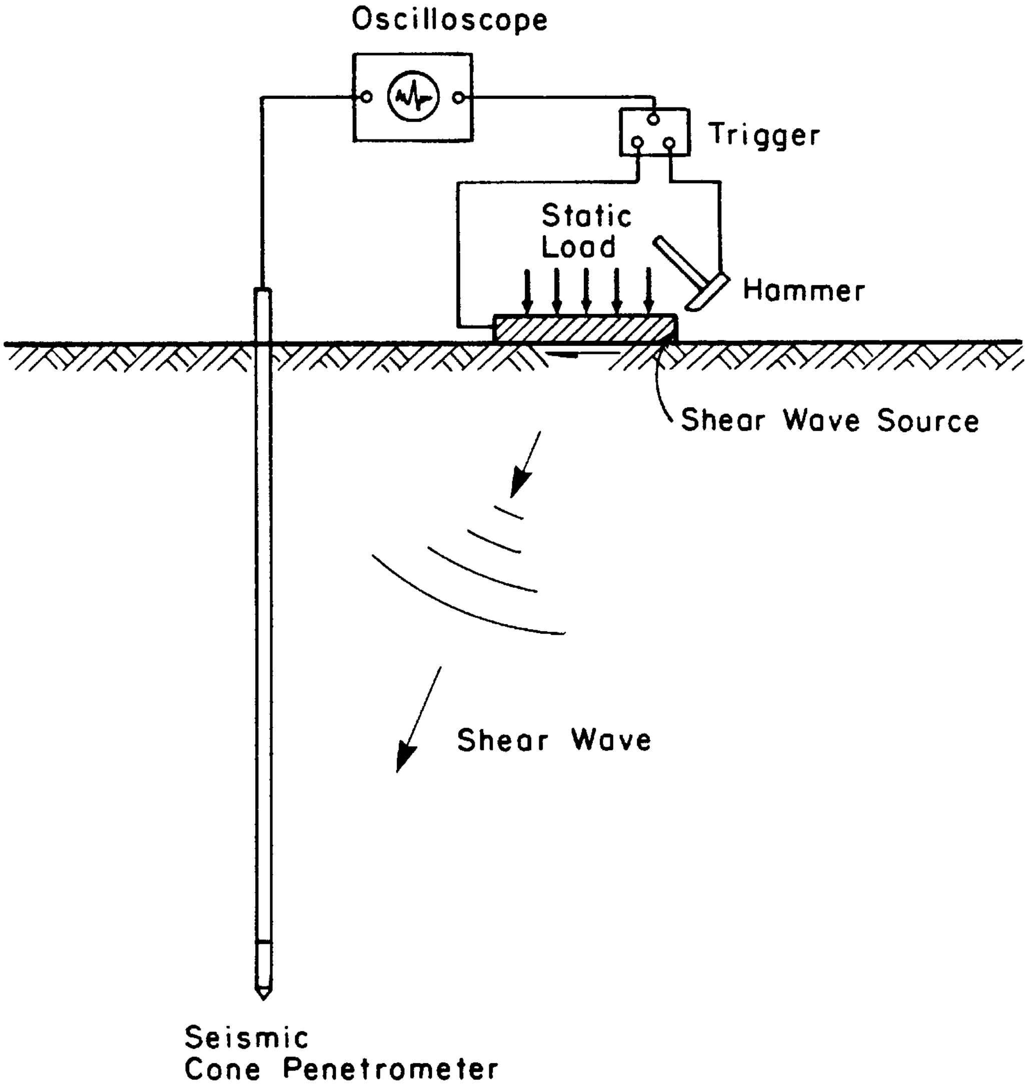

Fig. 2. Schematic Layout of Downhole Seismic Cone Penetration Test.

rigid beam or platform, steel jacketed and weighted to the ground. It may be struck with a sledge hammer as shown in Fig. 2. 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 meters of the cone hole. The beam should be rigidly placed on the ground so that no energy losses should occur due to plastic shearing of the soil beneath the beam.

For the offshore environment, the generation of an effective shear source is more complex. For deep offshore investigations (depth > 30 m), cone penetration testing is usually carried out using either downhole devices or seabed supported devices. It should be possible to incorporate an automatic shear wave source, similar to that used onshore, on existing seabed devices. The downhole devices could also incorporate a similar seabed device to generate shear waves. For the shallow offshore environment, it should be possible to manufacture a simple shear source to be lowered to the seabed. It is possible to generate shear waves in the seabed soils by detonation of an energy source in the water. Further details of this method are given later in the paper. The generation of an effective shear source is currently an area of intense research.

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 as shown in Fig. 3. Fig. 3 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 White (1965),

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

Analysis of the existing field data shows 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 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. The arrival time from source to detector is converted vectorially to a vertical travel path. The difference between

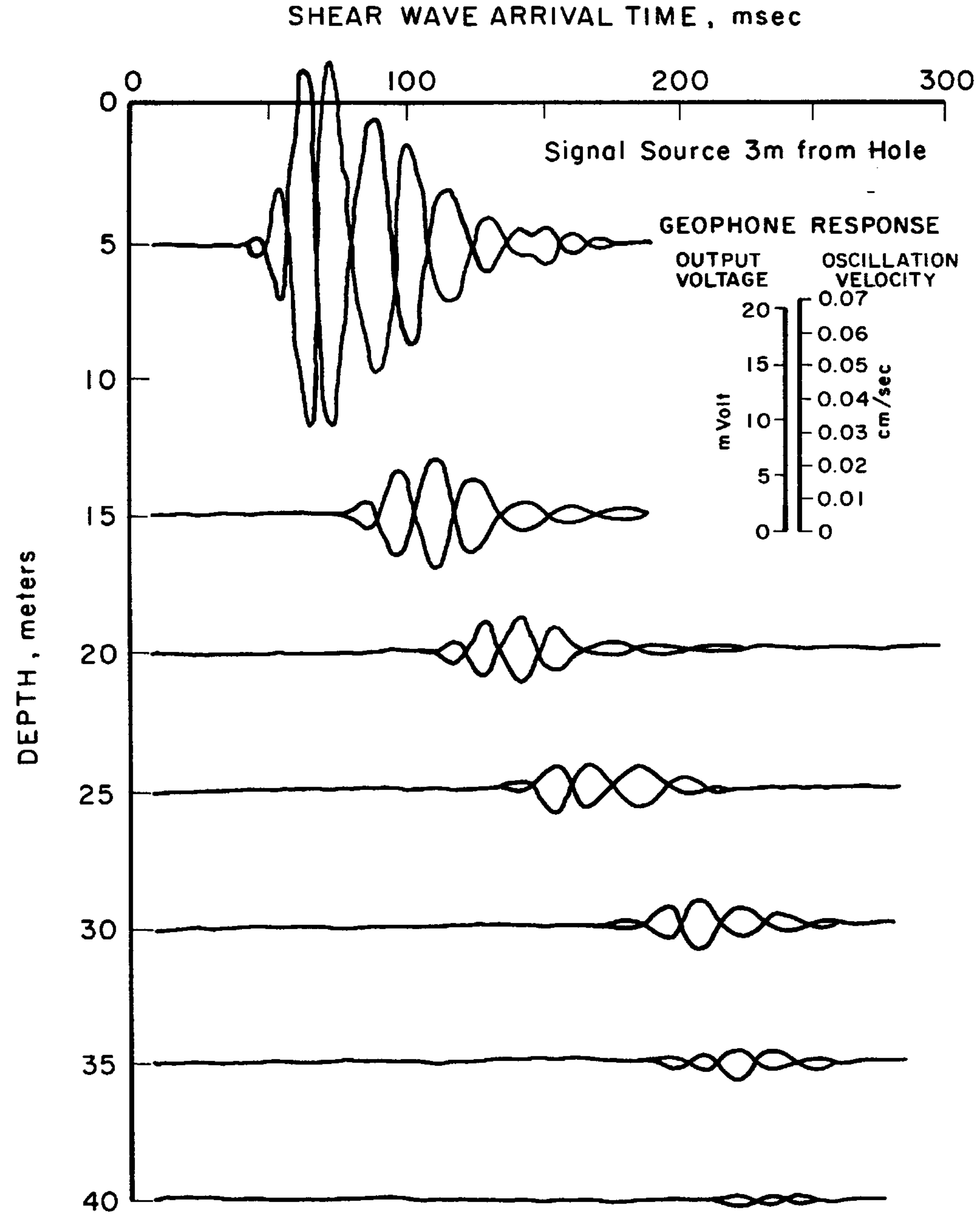

Fig. 3. Quantitative Comparison of Geophone Response Amplitude and Relative Shear Wave Travel Times from Seismic Cone Penetration Test.

successive 1 m depth measurements of vertical travel path time is used to determine the shear wave travel time over the 1 m interval of depth. 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 (1978). 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 was placed 1 m vertically above the first geophone (Rice, 1984). This equipment modification allowed true interval surveys to be carried out and 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 showed 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.

Onshore 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.

A comparison between shear wave velocities measured using the seismic cone penetration test and conventional crosshole techniques is shown in Figs. 4 and 5. Seismic CPT tests were performed at several sites in Norway with the cooperation of the Norwegian Geotechnical Institute (NGI) (Eidsmoen et al., 1984). These sites are well documented sites with extensive field and laboratory data.

The Holmen site (Fig. 4) consists of loose, medium to coarse sand to a depth of 25 m. On average the two seismic shear wave velocity profiles are almost identical at this site showing little, if any, discrepancy between the SCPT downhole and conventional cross-hole.

The Museumsparken site (Fig. 5) consists of the well documented Drammen clay to a depth of 15 m. Again the two seismic profiles compare very favourably.

Offshore Seismic CPT Results

Seismic cone penetration tests were performed in the shallow offshore area of the Canadian Beaufort Sea. Testing was performed during the winter of 1985 using the approximately 2 m thick sea ice as a stable platform. The depth of water beneath the ice was generally less than 8 m.

Several seismic sources were tested to evaluate their effectiveness in the generation of compressional (P) and shear (S) waves. Explosive caps were the predominant seismic source. The explosive caps were generally placed in the water beneath the ice. When the sea-ice extended to the seafloor (i.e. no water beneath ice) the seismic signal was generated by striking the rear support pads of the cone vehicle with a 7 kg hammer, as shown schematically in Fig. 2. Using the hammer technique, it was possible to generate polarized shear (S) waves with very little compressional (P) waves.

Seismic velocities were calculated using the pseudo-time interval

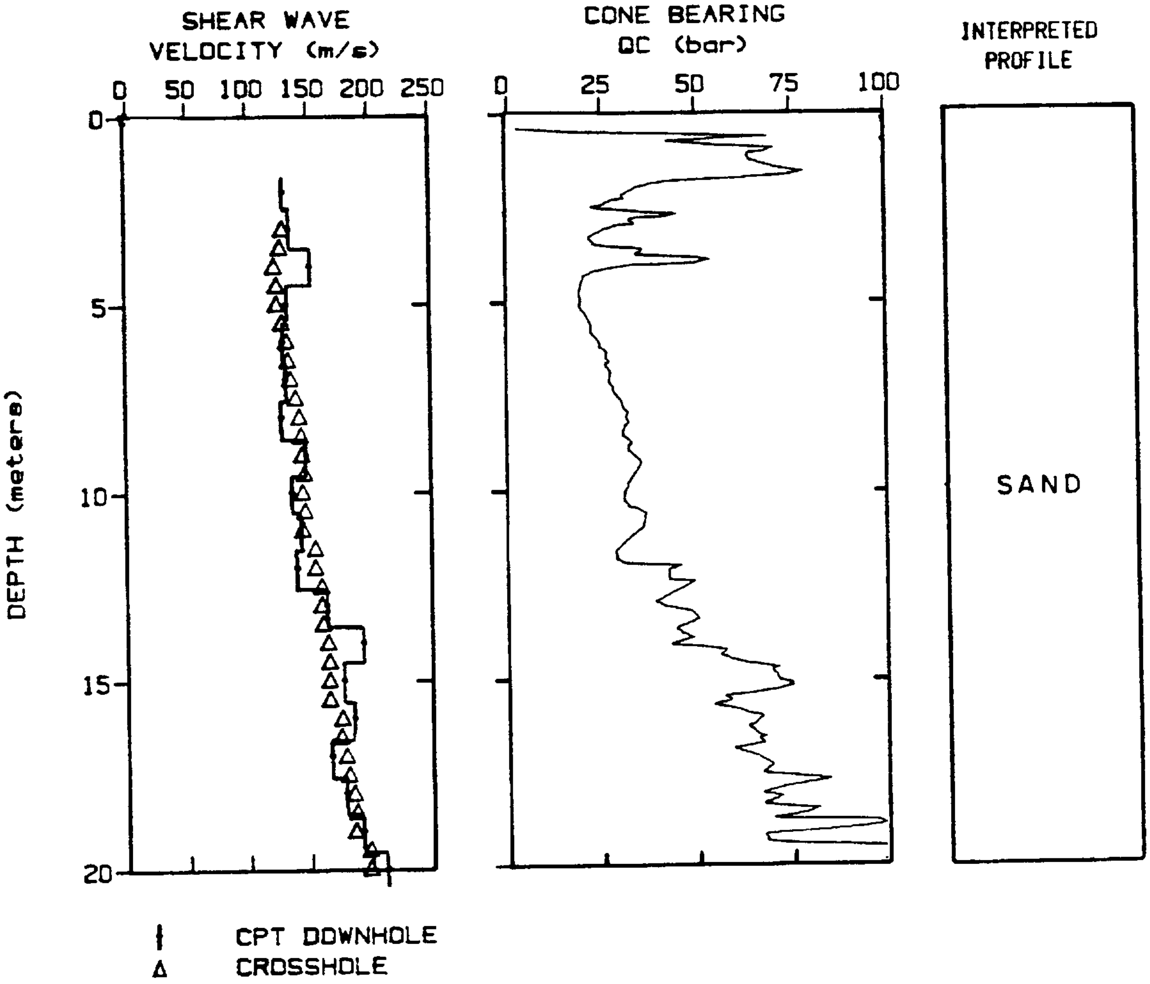

Fig. 4. COMPARISON OF SEISMIC CPT DOWNHOLE AND CROSSHOLE DATA AT HOLMEN SITE, DRAMMEN, NORWAY

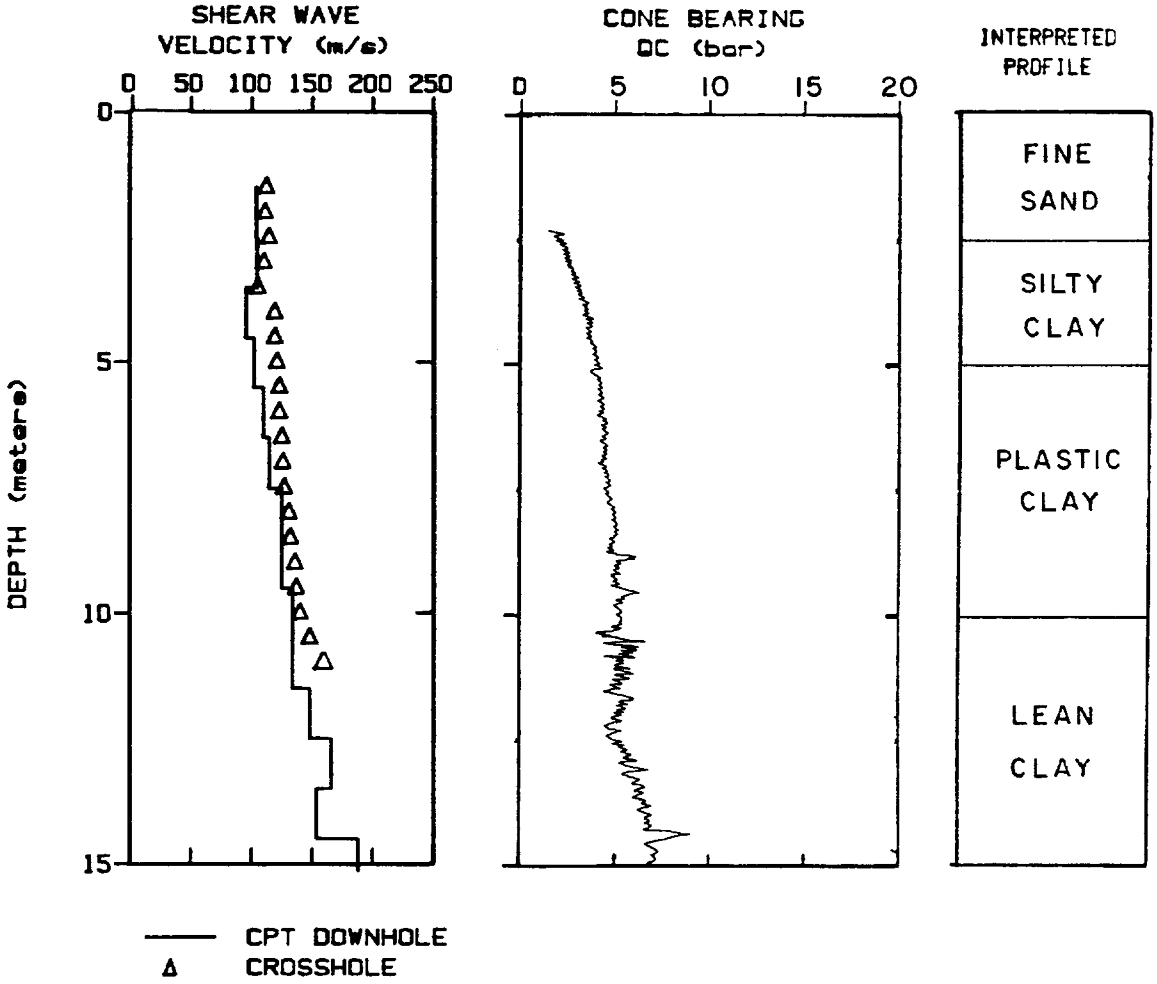

Fig. 5. Comparison of Seismic CPT Downhole and Crosshole Data at Museumsparken Site, Drammen, Norway.

technique. Generally, seismic measurements were made at 1 m intervals starting approximately 2 m below mudline.

The average P-wave velocity for most of the tests was close to 1500 m/s. However, calculations using the pseudo-time interval method for high P-wave velocities are sensitive to small variations in seismic cap location. In most saturated soils, the compression wave velocity is dominated by the compression wave velocity of water (i.e. 1500 m/s).

Initially, difficulty was experienced in identifying the shear wave arrivals using the seismic cap explosive source. Figure 6 illustrates the geophone response from a series of tests over the depth range of 4 m to 18 m below mudline for a typical sounding. The fast, high frequency P-wave arrivals are clearly visible. The slower, low frequency S-wave arrivals are also visible in Fig. 6. The average shear (S) and compression wave (P) velocities shown in Fig. 6 are 220 m/s and 1600 m/s, respectively. It is interesting to note the reflected P-wave arrivals in Fig. 6. The depth of water beneath the sea-ice at that location was less than 1 m. It appears the P-wave is reflected off the permafrost that was at a depth of 18.4 m below mudline then reflected again off the sea-ice. There also appears to be a reflected S-wave produced as the P-wave reaches the permafrost.

At one location, the depth to mudline increased rapidly over a short distance. This enabled the hammer technique to be used where the sea-ice extended down to and into the seabed and also to use the explosive cap source nearby where water existed beneath the sea-ice. A comparison of the shear wave velocities measured using the hammer source and the seismic cap source is shown in Fig. 7. Good comparison

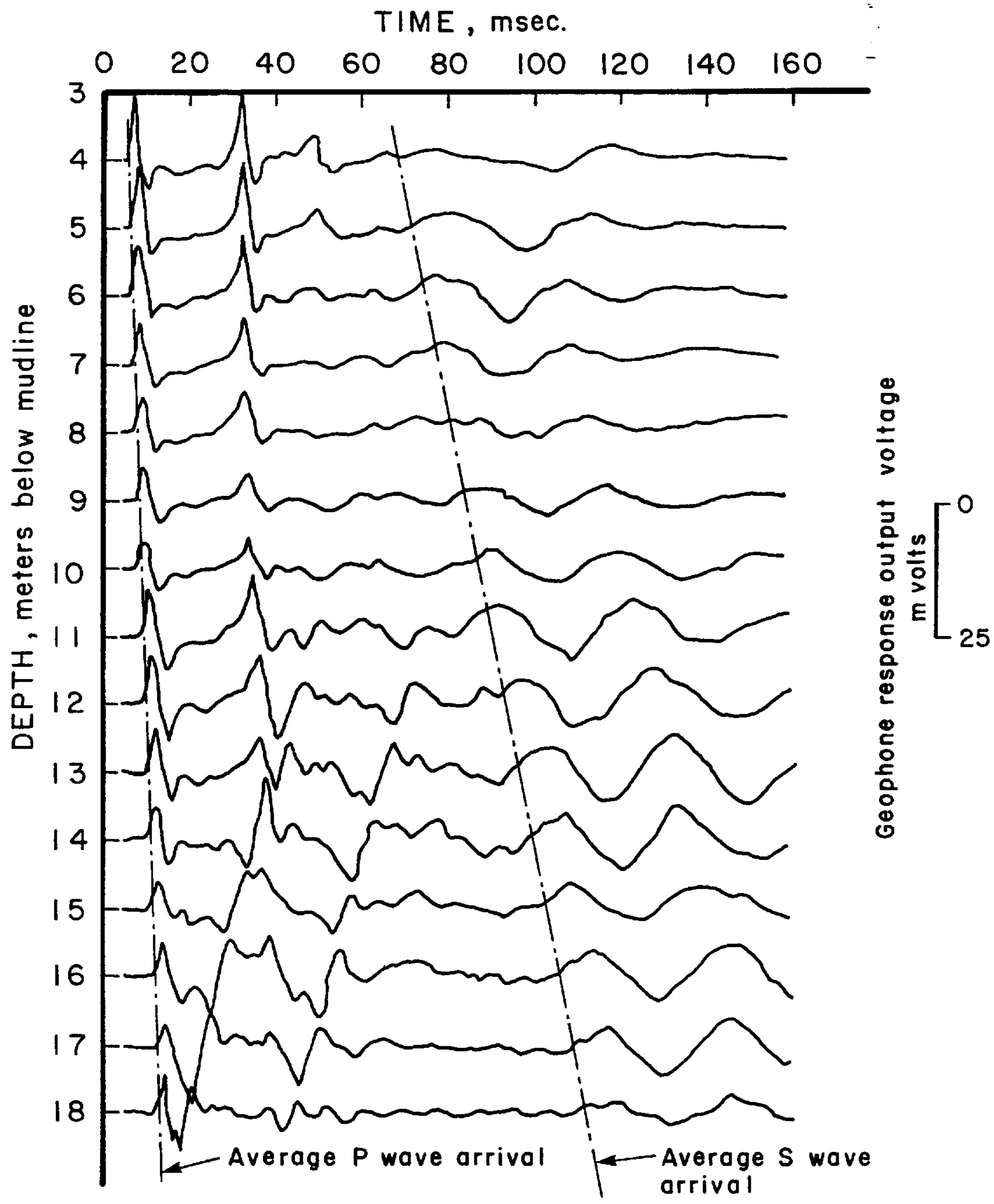

Fig. 6. Geophone Response from a Series of Seismic Tests During a Single Seismic CPT Profile in the Shallow Canadian Beaufort Sea.

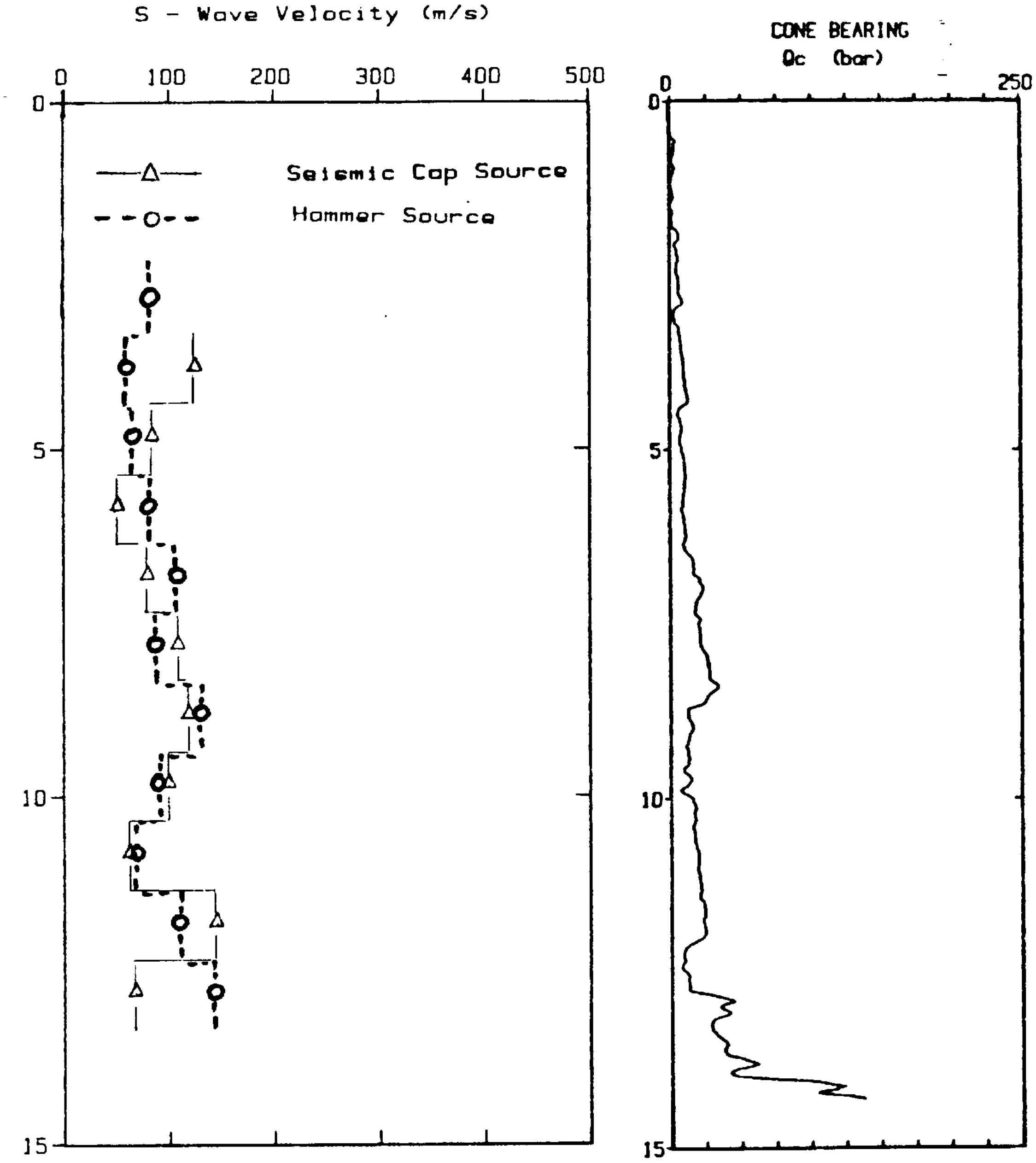

Fig. 7. Comparison of Shear Wave Velocities Measured Using Hammer Source and Seismic Cap Source.

was achieved between the hammer source data and the seismic cap data. This provided some confidence in the selection of shear wave arrivals using the seismic cap source.

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 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.

A current area of research is to investigate the full application of SCPT data. Comparisons are presently underway between SCPT data and self-bored pressuremeter, crosshole, flat plate dilatometer, screw plate and laboratory test results from several onshore sites.

Comparison of onshore 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 seismic CPT shows particular promise for use off-shore where CPT equipment is already used extensively and where shear wave velocity measurements would be of value in design of large off-shore platforms.

Preliminary test results using the seismic CPT in the shallow offshore environment show that the simple procedure of detonating explosive seismic caps in the water can provide adequate data provided care and experience is used in the data interpretation. However, it should be possible to incorporate a simple automatic hammer type seismic source onto existing seabed cone penetration devices. Further research is presently underway to investigate various sources and receivers for offshore work.

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