

A Seismic Cone Penetrometer
to Measure Engineering Properties of Soil

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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. The finite element method of analysis is becoming a standard tool in dynamic and static design of complex structures both on and off-shore. In order to obtain soil data for analysis, new field and laboratory testing techniques have been developed.

Virtually all soils show non-linear stress strain behaviour even at very low strains. Therefore, a knowledge of the stress strain behaviour is necessary in connection with many engineering geotechnical problems. Fig. 1 shows a typical stress strain curve where the initial modulus is equivalent to the maximum shear modulus, G_{max} . The typical nonlinear stress strain relationship of soil can be represented by a hyperbolic curve with a knowledge of the maximum shear modulus and the shear strength. Research has shown that the shear modulus decreases with increasing shear strain similar to that shown for sands in Fig. 2. The shear modulus is almost constant at shear strains less than $10^{-3}\%$ and is generally referred to as the dynamic shear modulus, G_{max} . The shear modulus is a fundamental soil property which relates shear deformation to shear loading.

In the field the cross-hole or down-hole method has become the standard technique for dynamic testing to determine G_{max} . A polarized shear wave is generated in one borehole (or at the surface) and the time is measured for the shear wave to travel to the geophone in the borehole. Elastic theory relates the shear modulus, G , soil density, ρ , and shear wave velocity, V_s as follows:

$$G = \rho V_s^2$$

Hence the shear modulus can be determined using in-situ seismic methods for the determination of the shear wave velocity. The shear strain amplitude

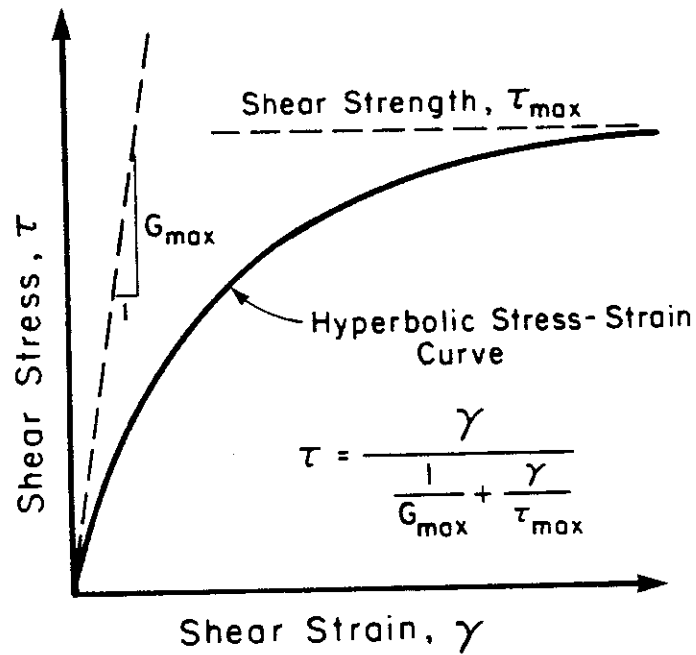


Fig. 1. Hyperbolic Stress-Strain Curve for Soil.

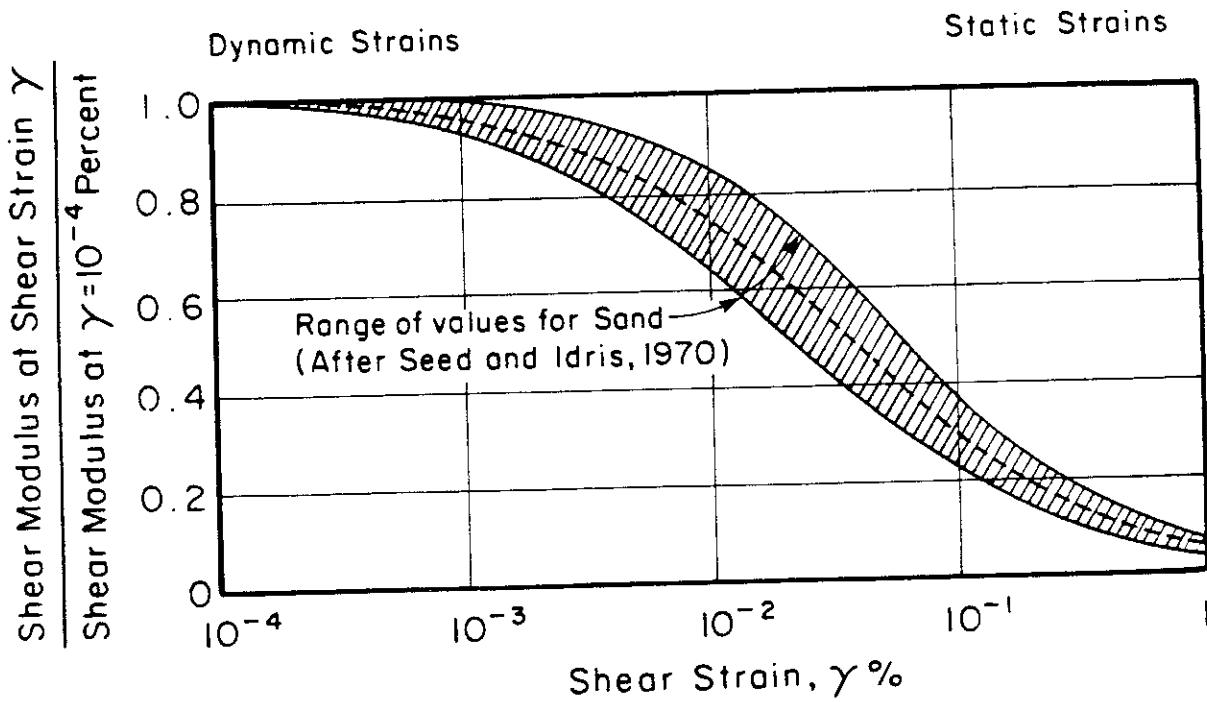


Fig. 2. Decrease in Shear Modulus with Increasing Shear Strain for Sands (After Seed and Idriss, 1970).

in such a test is usually low and of the order of $10^{-4}\%$. 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 almost impossible for off-shore use.

A new device, called the seismic cone penetrometer, can dramatically reduce the cost associated with seismic testing.

Seismic Cone Penetrometer

The cone penetrometer is already used extensively off-shore and on-shore 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 (ASTM, 1979). A friction sleeve, located above the conical tip, has a standard area of 150 cm^2 . The friction sleeve has the same diameter as the conical tip, i.e. 35.7 mm.

Electronic penetrometers have built-in load cells that record separately end resistance, q_c , and side friction, f_s . Bonded strain gauges are most commonly used for load cells, because of their simplicity and ruggedness. Pore pressure transducers have also been added to measure the dynamic pore pressures during penetration. The cone penetrometer is pushed at the standard rate of 2 cm/sec. Standard 1 m long rods are used to push the cone penetrometer into the soil. A cable, prethreaded up the center of the hollow push rods, connects the cone to the data acquisition system at ground surface.

Full details of the design of an electronic cone are given by Campanella and Robertson (1981). The piezometer-friction cone is regarded as the premier tool for the continuous logging of soil stratigraphy and shear strength. An example of the extensive data obtained from a piezometer-friction cone is shown in Fig. 3. The cone data can be interpreted to give a continuous prediction of soil type and shear strength (Robertson and Campanella, 1983). Predictions of soil stiffness (modulus) from the cone resistance are rather poor with a large potential error. The introduction of seismic measurements into the cone enables the specific measurement of the dynamic modulus. The measurement of soil strength and modulus provides a knowledge of the complete stress-strain relationship required for the complex finite element analyses.

To obtain the measurement of dynamic shear modulus a triaxial package

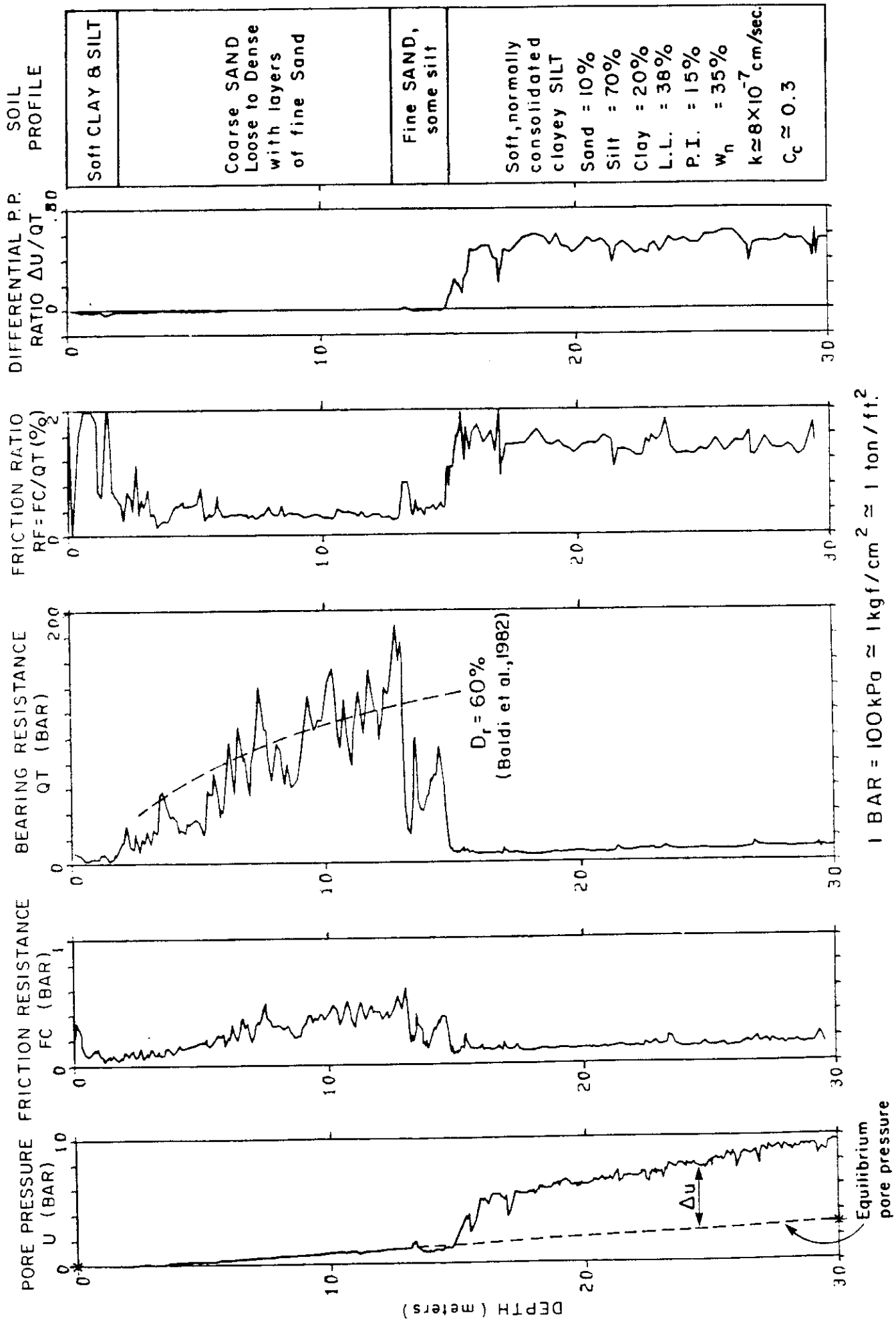


Fig. 3. Example of Piezometer-Friction Cone Data.

of small, rugged seismometers has been incorporated into the cone penetrometer. The seismometers are Geospace GSC-14-L3 with a standard natural frequency of 28 Hz. The horizontal seismometers are oriented in radial and transverse orientation to the signal source. The transverse seismometers are placed to detect the horizontal component of the shear wave arrivals and the vertical seismometer is placed to detect the vertical component of the shear wave arrivals if the cone were to be used in crosshole configuration or if a vertical shear source is used. A schematic diagram showing the layout of the standard downhole technique is shown in Fig. 4.

A suitable seismic signal source should preferentially generate large amplitude shear wave 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 plank, weighted to the ground and struck with a sledge hammer as shown in Fig. 4.

The design and construction of the seismometer carrier provides a snug seating for the triaxial 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 seismometers are recorded on a Nicolet 4094 digital oscilloscope with floppy disk capability. This unit has a 16 bit analog to digital signal resolution, very accurate timing capability and trigger delay capacity. The 16 bit oscilloscope is capable of recording clear shear wave traces from single hammer impulses to depths of 40 metres, as shown in Fig. 5.

Seismic Cone Penetrometer Results

Downhole seismic shear wave velocity measurements were made at the site shown in Fig. 3. The seismic cone penetrometer was pushed into the soil at a constant rate of 2 cm/sec. At 1 m intervals, the penetration was stopped and shear waves generated at the surface by hitting a plank with a sledge hammer. Fig. 5 provides a quantitative comparison of the primary horizontal geophone response amplitude and relative shear wave travel times

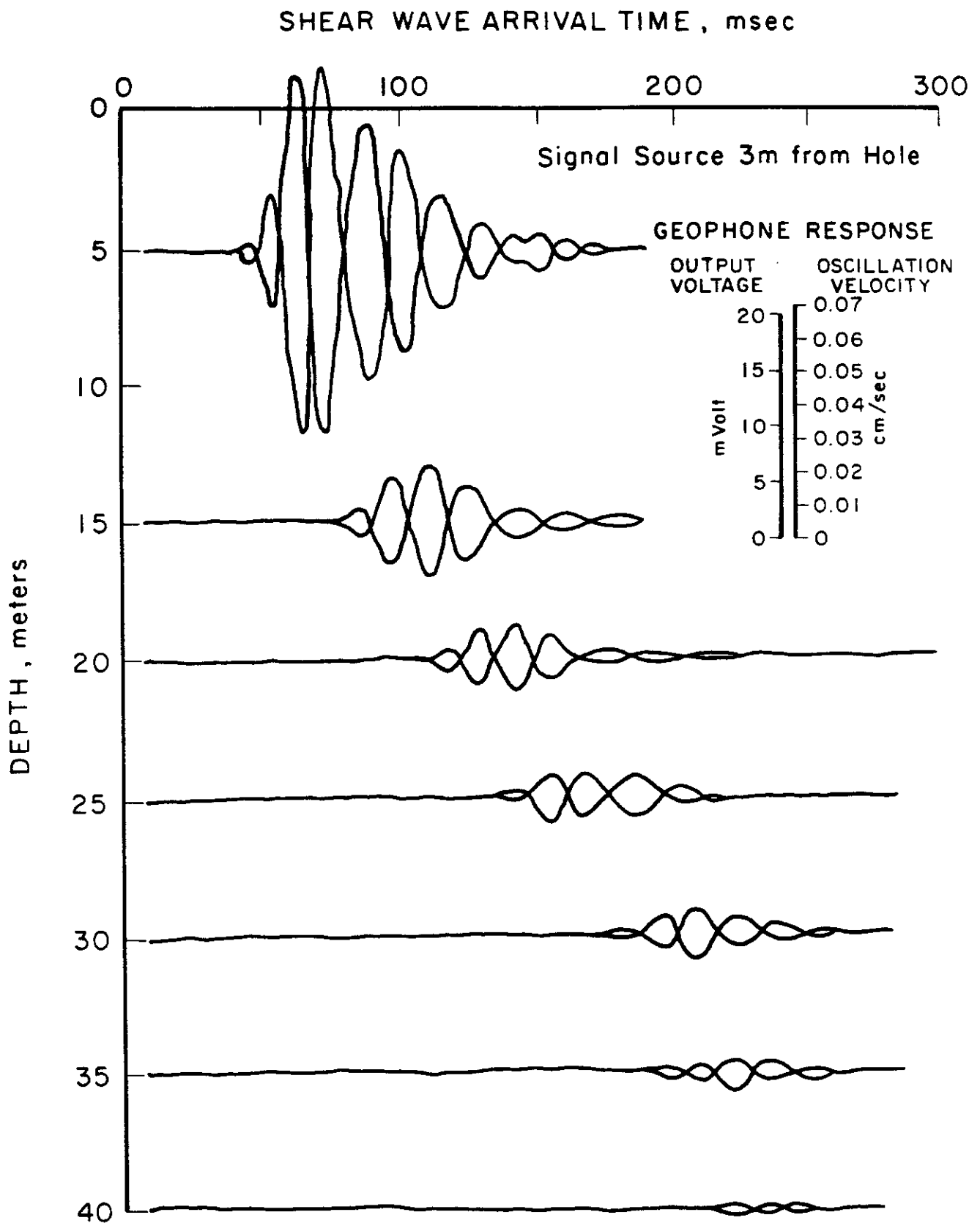


Fig. 5. Quantitative Comparison of Geophone Response Amplitude and Relative Shear Wave Travel Times from Seismic Cone Penetrometer.

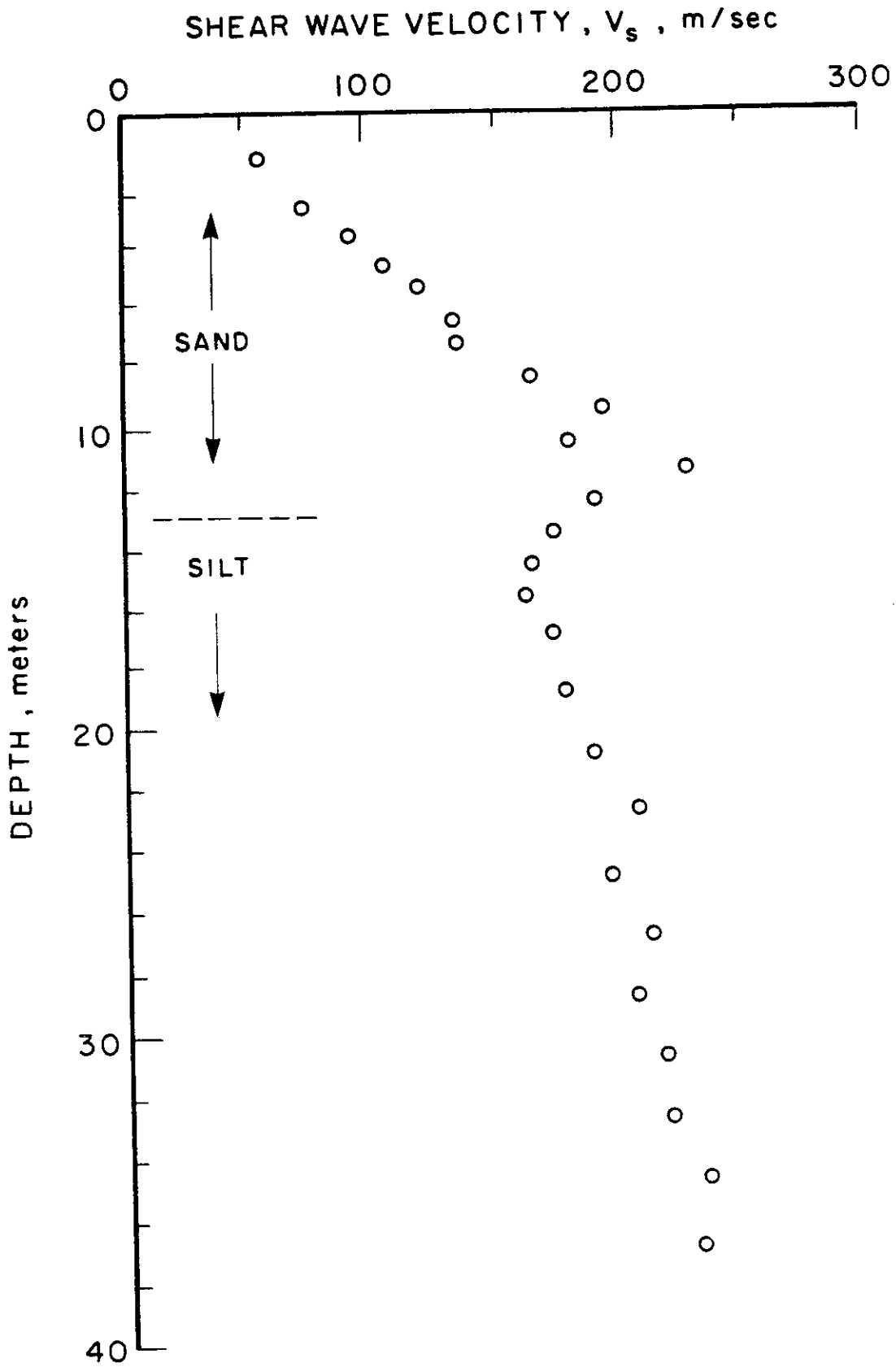


Fig. 6. Calculated Shear Wave Velocity Profile From Seismic Cone Penetrometer.

with depth. The geophone output voltage is directly related to the particle oscillation velocity as shown on the inset scales.

It has been found that the time for the first cross-over point (shear wave changes sign) provides the most repeatable reference arrival time, which is converted vectorially to a vertical travel path. The difference between successive 1 meter depth measurements of reference arrival time for vertical travel path is used to determine the shear wave velocity 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. Since the shear wave velocity is squared to calculate G_{\max} , a high priority must be given to the accuracy of travel time measurements.

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 velocity, and therefore maximum shear modulus, increases with depth. Also, the rate of increase with depth is very much higher in the sand than in the silt.

The reasonably rapid advance and withdrawal procedure using the seismic cone penetrometer allows a fast determination of soil type, strength and stiffness in one sounding. 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.

References

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