Techniques for Offshore *in situ* Geotechnical Tests

by

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Introduction

The application of soil mechanics in ocean engineering are numerous: (1) design and construction aspects such as harbor protection facilities, foundations for offshore mining and drilling platforms, oil storage reservoirs, recreational facilities, industrial plants, radar towers, naval installations, underwater pipelines, cables and tubes, man-made island, manned and unmanned installations; (2) stability analysis aspects such as submarine slopes, erosion, and transport of beach sands, silting of harbors deepening of navigation channels, scour around foundations placed under water; (3) salvage and rescue operations; and (4) mooring and anchoring in ocean sediments.

The design of foundations for sea floor installations as well as most other applications of soil mechanics to ocean engineering requires detailed information on the strength properties of sea floor soils. This information can be obtained either by sampling (for subsequent testing) or directly from *in situ* testing. A variety of sampling methods is available for ocean floor applications as summarized by Noorany (1971). These sampling methods range from shallow penetration sampling (of a few feet) by conventional type gravity and free fall corer to deep penetration sampling by wire line sampler which can collect samples to a depth of 400 feet (122 meters) below the sea floor in water depths above 1,000 feet (305 meters). The present sampling techniques, however, are known to disturb the soil and provide a poor sample for engineering analysis especially for shear-strength testing, which is a useful parameter in assessing *in situ* strength profile (Anderson, et al. 1965, Kraft, et al. 1976, Noorany 1971, Richards and Keller 1961, and Richards and Parker 1967). Based on analysis of data from several sites in the Gulf of Mexico, Kraft, et al. (1976), have concluded that *in situ* vane measured strength is not a constant multiple of the vane strength measured in laboratory on collected cores. The ratio of *in situ* vane strength to laboratory vane strength ranged from one to more than three. *Lee (1973) and* McClelland (1975) observed the variations of 30 to 50 per cent over laboratory and *in situ* vane test results.

To minimize the sample disturbance in cores, Richards and Parker (1967) recommend a design criterion of a sampler. In the event a 'perfect' soil sampler is available, it may be possible to minimize the physical disturbance of the sample. However, there are other disturbances caused to the soil sample during sampling from deep ocean bottom. A few of these are:

(*i*) Core deformation caused by removal of *in situ* stresses (Richards) and Parker 1967).

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(*ii*) Piston movement during sampling (Anderson, *et al.* 1965).

(*iii*) Change in the geochemical properties of the sample (Jerbo 1967).

(*iv*) Organic growth caused by temperature and other environmental changes (Noorany 1971).

(*v*) Formation of gas bubbles in the pore water (Vey and Nelson 1967).

(*vi*) Expansion of water in the pore caused by pressure reduction (Vey and Nelson 1967).

When the soil sample is raised from the sea floor to the surface, the volume of pore water increases approximately 1.4 per cent per 10,000 feet (3,048 meters) of elevation and causes an expansion of the sample. In addition, as pore water stress decreases from the *in situ* value to tension, gas bubbles are sometimes formed and cause further expansion of the sample. The influence of these expansions on the strength of the submarine sample has not yet been determined. Since many other problems related to the effect of stress release and disturbance have been understood by past research (Emrich 1971, Ladd and Lambe 1964. Ladd and Varallyay 1965, and Noorany and Seed 1965), it appears that the change in pore water pressure and the possibility of bubbling in the pore water must be carefully investigated for marine soils before the measured sample properties can be considered to represent the *in situ* values.

The intention of the foregoing discussion is to recognize factors which affect the quality of samples so that further research may be initiated with the objective of developing some correlation by which the *in situ* strength value can be assessed from laboratory test results. In recognition of the many practical limitations confronting any improvement in sampling and analysis procedures in the near future, it is suggested that, as a means of enhancing data quality, soil strength properties be measured *in situ*. This paper describes some of the possible techniques of accomplishing such strength measurements attempted in recent years.

In situ Tests

The *in situ* measurement or estimation of an ocean floor soil's strength can be carried out directly, or it may, in certain circumstances, be made indirectly. The following two classes of measurement will be considered separately: (1) Direct Methods, and (2) Indirect Methods.

Direct Methods

A variety of techniques used for terrestrial *in situ* strength measurements is available for adaptation to ocean floor work. However, most of the techniques need some degree of modification to overcome the environmental constraints. New techniques are, therefore, being considered in view of special requirements imposed by the environment, industry's needs, and cost effectiveness.

There are two broad categories of direct *in situ* soil testing at sea. One category consists of shallow penetration *in situ* testing usually extending less than ten feet below the ocean bottom. The other category consists of deep penetration *in situ* testing in order to reach a desired exploration objective substantially below the sea floor, usually tens of feet. The two categories will be considered herein. The methods employed include the following:

I. Shallow penetration in situ testing

(*a*) Vane shear test

(*b*) Static cone penetration test

(*c*) Plate bearing test

(*d*) Dynamic penetration test

II. Deep penetration in situ testing

(*a*) Wire line vane test

(*b*) Continuous and wire line static penetration test

(*c*) Pressuremeter test

Shallow penetration *in situ* testing

The instruments in this category of testing have a very limited penetration capacity, usually less than ten feet, which imposes a serious limitation on their usefulness. However, there are a number of underwater activities, such as pipeline and cable projects, harbor dredging, and light underwater installations, which require *in situ* strength testing of near-surface deposits only. The techniques commonly used for shallow penetration *in situ* investigations are described below.

(*a*) *Vane Shear Test*

A vane shear test by measuring the maximum torque created on a set of square or rectangular vanes rotated in the soil is a common means of determining the shear strength of cohesive soils. The primary limitation of this test is that it is not applicable to sand and inorganic silt.

Fenske (1957) first reported the use of vane shearing tests in the Gulf of Mexico for measuring underwater *in situ* soil strength properties. Taylor and Demars (1970) have developed one of the very versatile underwater *in situ* testing instruments, "The Deep Ocean Test in Place and Observation System" (DOTIPOS), for measuring shear strength using either a vane shearing device or static cone penetrometer, The DOTIPOS is pyramid shaped having an 18-foot (549 cm.) square base and a height of 17.5 feet (533 cm.). It is supported on three 4×4-foot (122×122 cm.) bearing pads and weighs approximately six thousand pounds in air. This instrument is capable of measuring shear strength to a sediment depth of ten feet below the mudline. The performance of this vane device has been tested at several sites ranging in water depths of 100 to 1,200 feet (30 to 366 meters).

Another research submersible platform developed by Richards, *et al.* (1971), has been designed to support a remote controlled vane having a penetration depth of ten feet (305 cm.) in water depths up to 15,000 feet (4,572 meters). The platform is about seven-feet (213 cm.) wide at the base and has a 12-foot (365 cm.) high tower. This equipment has performed satisfactorily in water depths ranging from 300 feet (91 meters) in the Gulf of Mexico to 3,200 feet (975 meters) at Exuma Sound, Bahamas.

In addition, several diver-operated, vane shear testing devices have been reported (Inderbitzen and Simpson 1971 and McNary and Frohlich

1970) for *in situ* testing of surficial sediment deposits in water depths of generally less than 100 feet (30 meters). A remote underwater manipulator (RUM), a bottom crawling vehicle developed by the Marine Physical Laboratory of Scripps Institution of Oceanography (Anderson, et al. 1971), for use as a research tool in sea floor soil investigation, has an operational depth of 6,000 feet (1,829 meters) of water. The crawler has been developed for *in situ* soil trafficability studies and has been instrumented to perform cone penetrometer and vane shear tests to a depth of 2 feet (61 cm.) below mud line. These devices have a limited use because of very shallow penetration depth.

(*b*) *Static Cone Penetration Test*

In terrestrial use, static cone penetration test is described as driving a cone-tipped cylindrical rod into soil at constant low speed whereby the cone thrust or both cone thrust and local side friction are measured either mechanically or electrically. Although this test has not been standardized formally, a generally accepted practice has been developed for terrestrial use (Begemann 1965). The cone has a base area of 1.55 sq. in. (10 sq. cm.) and an apex of 60 degrees. The friction sleeve has generally a surface area of 23.25 sq. in. (150 sq. cm.). The adopted rate of penetration is of the order of 0.6 to 0.8 in./sec (1.5 to 2 cm./sec). For advancing the cone, hollow rods are used with an outside diameter of 1.4 inches (36 mm.). usually in sections of 3.3 feet (1 meter).

Special features of cone penetrometer tests, in addition to testing soils in their natural environment, are the continuous information produced, allowing detection of changes in soil properties that might be missed by intermittent testing or sampling, and information which permits strength evaluations of cohesionless, as well as cohesive soil formations.

As described previously, DOTIPOS (Taylor and Demars 1970) has also been devised to perform cone penetrometer tests to a depth of ten feet (305 cm.) below the mud line. The performance of the cone device has been tested at various sites in water depths up to a 5,600 feet (1,705 meters). Hirst, et al. (1971), have reported the development of static cone penetrometer device which is operated from a submersible platform. However, the limited negative buoyancy that can be safely developed by the submersible platform restricted the depth of sediment penetration to 3.5 feet (107 cm.). For achieving a significant penetration depth, the submersible platform system needs alternative methods of developing the needed reaction (for example, by deploying anchors).

(*c*) *Plate Bearing Test*

Harrison and Richardson (1967) have performed the plate bearing test in shallow water (16 to 20 feet; 487 to 609 cm. deep) in the conventional manner. The plate was loaded with a hydraulic jack and the balancing reactions were provided with the help of massive concrete blocks. However, this system is not suitable for deepwater testing unless some modifications are made. Kretschmer and Lee (1969) have reported a device, developed by Naval Civil Engineering Laboratory, for performing *in situ* plate bearing tests on sea floor sediments. It is a very compact, electronically operated, remote controlled device that is capable of performing the test in water depths of up to 14,000 feet (4,263 meters). The equipment has approximately 12-foot (365.4 cm.) square base with a height of approximately seven feet (213 cm.) and weighs four tons in air. It can accommodate bearing plates ranging in size from nine inches (23 cm.) to 1.5 feet

(46 cm.) in diameter and can apply a maximum load of 6,000 lbs. (2,730 Kg.). From the analysis of the test results obtained with it, it has been established that the traditional soil mechanics concept involving elastic and bearing capacity theories appears to be applicable to analysis of weak upper strata of sea floor soils.

(*d*) *Dynamic Penetration Test*

In recent years, several studies on the penetration of objects at low and high velocities into the ocean floor have been carried out in order to estimate the strength properties of marine soils (Dayal, et al. 1975, Migliore and Lee 1971, Scott 1967, and Beard 1976). Scott (1967) described the use of an accelerometer-monitored corer which, while collecting the soil sample, records simultaneously the acceleration signatures of the corer. With the recorded acceleration, the velocity and displacement of the corer can be computed for its entire operation. This technique has been tried for both gravity and free fall types of corer. For the gravity type of corer, a simple mathematical relationship has been proposed for calculation of shearing resistance of soil from accelerometer signatures. Since the soil in which the penetration occurs is actually retained by the sampler, a comparison can be made between the soil shear strength and the value calculated from the accelerometer signatures.

Beard (1976) has reported an expendable type of free fall penetrometer using the Doppler Principle. The penetrometer, approximately 10 feet (305 cm.) long and about 3.5 inches (9 cm.) in diameter, houses an accelerometer and weighs about 365 lbs. (166 Kg.). This free fall penetrometer, when dropped from a ship can attain an impact velocity of 80 feet/sec. (24 meters/sec.) and penetrate approximately 30 feet (9 meters) in soft sediments in water depths up to 20,000 feet (6,100 meters).

It has been well recognized (McNeill 1972) that the penetrometer instrumented with accelerometer is a useful tool in tracing the velocity and depth of penetration. The results to date (1978) indicate that it is not possible to obtain *in situ* strength of the soil from accelerometer signatures alone. To overcome this problem, Dayal, et al. (1975), developed a modified version of free fall penetrometer which is instrumented to record cone thrust, sleeve friction, and acceleration/deceleration simultaneously and continuously up to the final depth of penetration. The operating principle of this penetrometer is similar to that used in the triggered corer. Figure 1a-c shows conceptual views of the three stages of the penetrometer operation. Using this system, the impact velocity can be preselected (up to terminal velocity) according to the requirements. Figure 1 gives a cross-sectional view of this penetrometer.

The penetrometer has been devised with three sensors : accelerometers, cone load cell, and friction sleeve load cell. With these sensors it is possible to measure *in situ* strength continuously up to penetrated depth. Numerous successful field trials have been made with this instrument. One test result is shown in Figure 2, which shows the depth vs. acceleration/deceleration, cone thrust, and sleeve friction profile. For additional information concerning the procedures for determining *in situ* strength, the reader is referred to paper by Dayal, et al. (1975). The initial field trials have indicated this penetrometer to be a promising tool for *in situ* strength determination of shallow sediment penetration. The primary advantages of this device are cost effectiveness, rapid test, and ease of

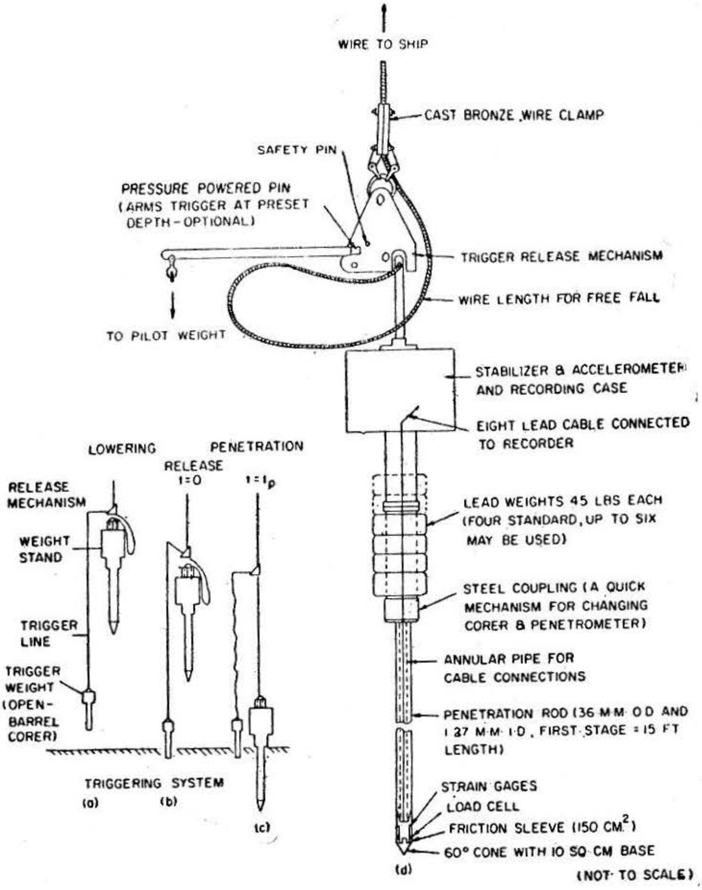


FIGURE 1 Marine impact penetrometer (After Dayal, et al, 1975)

handling in adverse weather conditions from a ship not equipped with elaborate lifting and winch facilities.

Deep Penetration *In Situ* Testing

(*a*) *Wire Line Vane Test*

Deep penetration vane tests were first performed by Fenske (1957) in the Gulf of Mexico with some success. In that investigation, vane shearing measurements to 254-foot (77 meters) penetration were made in 66 feet (20 meters) of water. A standard field vane was adopted for offshore work and proved successful for testing clays which ranged from soft to stiff. The primary limitation in this earlier technique in terms of current industry needs is that it requires a fixed platform.

A significant recent development is a remotely controlled wire line vane test device for measuring *in situ* strength of submarine soil at great depth described by Doyle, et al. (1971), and Kraft, et al. (1976). The remote vane is operated in conjunction with standard offshore drilling and coring operations, using 3-1/2-inch (8.9 cm.) internal flush drill pipe. To perform

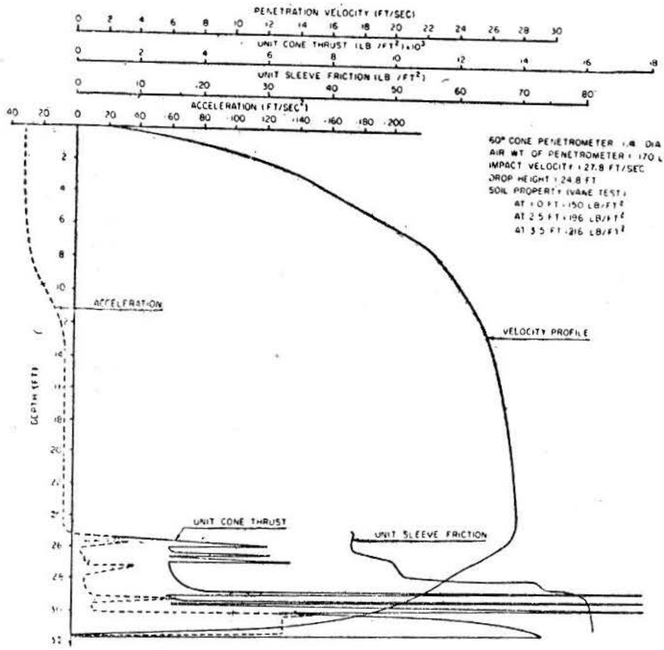


FIGURE 2 Field impact penetration test results (in shallow water) (After Dayal, et al, 1975)

a remote vane test (Figure 3), the boring is drilled to approximately two feet (61 cm.) above the desired test depth. The bit is then raised about six feet (183 cm.) above the bottom of the hole. The tool is lowered by a specially designed cable and reel assembly to the bottom of the hole. At this point, the pawls which are now located below the drill bit, are remotely extended by the operator. The drill pipe and bit are carefully lowered into the extended pawls, the vane is pushed to the desired depth in one rapid motion, and the drill pipe and bit are then raised several feet above the

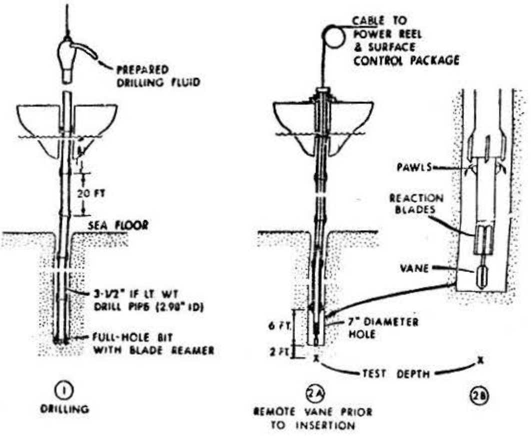


FIGURE 3 Operating sequence of remote vane (After Doyle, et al, 1971)

pawls. With the drill pipe removed from direct contact with the vane assembly and with slack in the vane conductor, the test is then performed with freedom from boat movement. After the test is completed, the pawls are retracted and the instrument reeled back up through the drill pipe. This device, which is in fourth generation of development, has been successfully tested in several offshore sites in the Gulf of Mexico to penetration in excess of 400 feet (122 meters) below the sea floor in water depths of more than 1,000 feet (305 meters).

(b) Continuous and Wire Line Static Penetration Test

The testing principles of continuous and wire line static penetration tests are the same as described for shallow penetration. Three versions of penetrometer rigs which are in use for offshore work are reported in literature. The two versions of penetrometer rigs, "Seacalf" and "Wison" developed by Fugro-Cesco B.V. (Ruiter and Fox 1975), have been widely used during geotechnical investigation programs for development of North Sea platforms. The latest model of the "Seacalf" penetrometer rig is shown in Figure 4. It is designed for lowering to the sea floor from the ship's derrick, through a 13-foot (4 meters) square drilling well. The electric penetrometer has been devised to measure simultaneously bearing and side friction. The penetrometer screws into the bottom of about thirty 3.3-foot (1 meter) long hollow sounding rods. These run through the hollow jacking piston and clamp in the rig and are held in tension by a wave-compensated wire line. After reaching the sea floor, the rods carrying the penetrometer are jacked hydraulically into the sea bed by oil pressure supplied through an electrohydraulic umbilical cable. The load cell signals from the penetrometer are transmitted to a chart recorder on deck. The jack piston has a stroke of 1.6 feet (48 cm.), the test being performed in 1.6-foot (48 cm) stages until achieving maximum penetration determined by a jack thrust capacity of about seven metric tons. Because of limited penetration capacity,

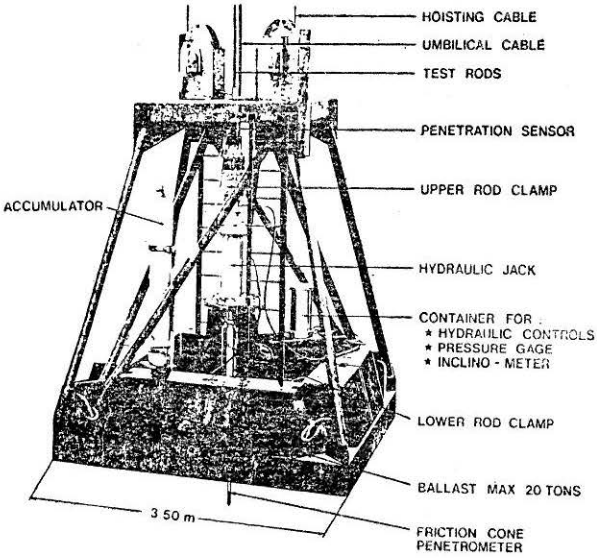


FIGURE 4 Seabed penetrometer rig "seacalf" (After Ruiter and Fox 1975)

this device is useful in providing data on nearsurface soils beneath such structures as gravity type of platforms.

At depths beyond the "Seacalf" testing capability, penetrometer tests are performed with the "Wison" wire line penetrometer (Zuidberg 1972). It is of cylindrical shape with a diameter of 3.5 inches (90 mm.), is lowered inside the drill string. It latches into the drilling bit adaptor and penetrates into the bottom of the hole, using the weight of drill pipe as reaction, limited by the wave compensator to three to four metric tons. The "Wison" contains a hollow jacking piston, through which the required length of rod is inserted. The device can make one single stroke of maximum 5 feet (1.5 meters) and, depending upon the hardness of soil, it can penetrate anywhere between the maximum stroke.

Figures 5*a* and 5*b* show the continuous penetration testing up to 75 feet (22.8 meters) followed by intermittent testing to a depth of 300 feet (91.4 meters) obtained from "Seacalf" and "Wison," respectively, at the North Sea location in water depths of more than 350 feet (107 metere).

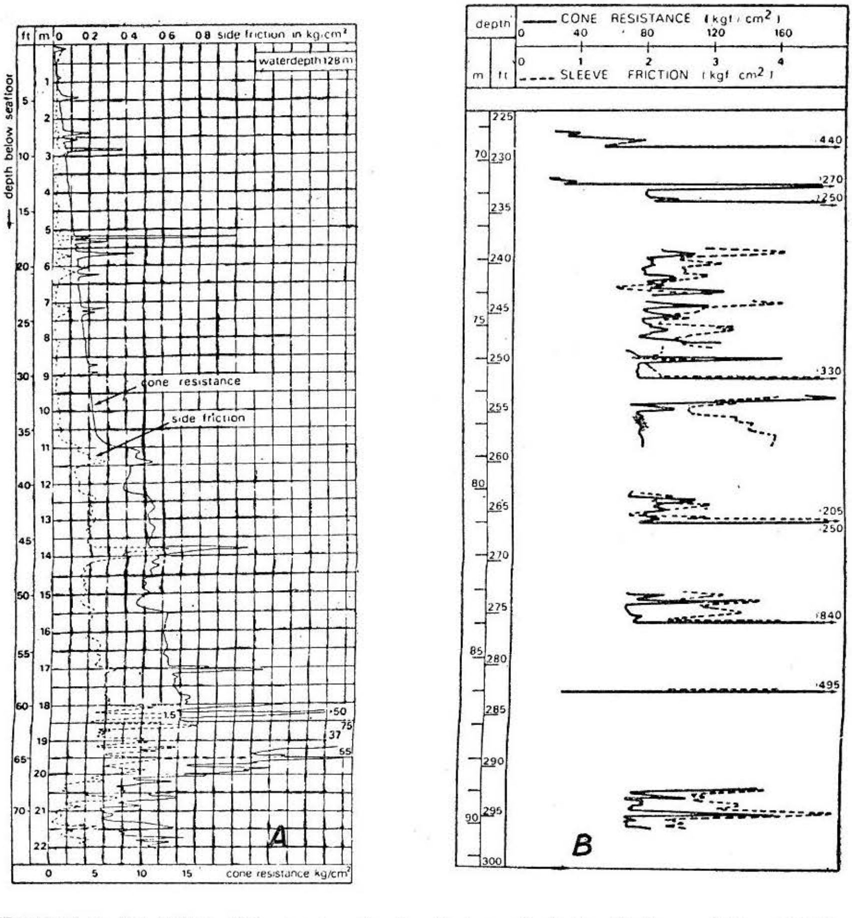


FIGURE 5 (*a*) "Seacalf" cone penetration test resuls (After Ruiter and Fox, 1975)
(*b*) "Wison" cone penetration test results (After Ruiter and Fox, 1975)

Another version of penetrometer rig "Stingray" has been developed by McClelland Engineers in collaboration with Norwegian Geotechnical Institute (Ferguson, et al. 1977 and McClelland 1975). It is a remotely controlled, hydraulically operated sea floor-bsaed unit which operates in conjunction with offshore drilling equipment to provide continuous cone bearing pressure and sleeve friction and high quality soil samples.

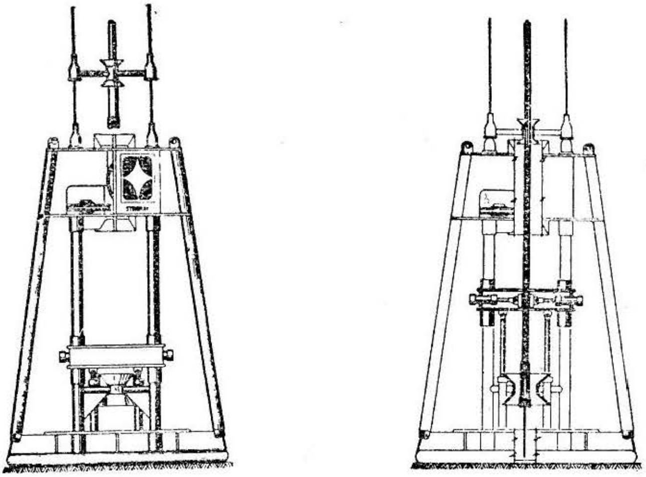
As illustrated in Figure 6*a*, the "Stingray" is initially placed on the sea floor to begin the operation. The two lifting lines then serve as a guidance system to lead drill pipe down into the jack, where the pipe is initially gripped and held about three feet (91.4 cm.) off bottom. The cone and about 20 feet (610 cm.) of cone rod are then lowered and locked into the bottom of the drill pipe (Figure 6*b*). Action of the "Stingray" jacking unit then forces penetration of the cone in increments of one to three feet until the rod length is fully utilized (Figure 6*c*). The cone and rod are then retrieved, and the drill pipe is used to drill down to a level just short of the cone's maximum penetration (Figure 6*d*). Thereafter, the process is repeated to any desired depth. If at any depth of penetration the penetrometer is stopped because of point refusal, drilling is continued past the level of maximum penetration prior to resumption of tests, resulting in a short gap in the record. This ability to continue testing below obstacles is a powerful feature of this tool, assuring the capability, for example, of testing a weak layer underlying a strong layer—a situation frequently encountered in North Sea site studies. This device holds promise for providing continuous cone penetration data to any required depth—as may be needed for example, for studies of seismic stability and improved analysis of high capacity piles.

This rig has been successfully tested at three marine borings located within extremely soft recent clays in the Gulf of Maxico. The interpreted results from one of these borings to 120-foot (36.6 meters) penetration is presented in Figure 7 together with *in situ* shear strength measurements made with the remote wire line vane and laboratory vane results from tests performed on samples taken in an adacent boring. Also included on the boring logs are soil descriptions and the results of some soil classification tests. An examination of Figure 7 indicates that *in situ* strengths obtained from cone penetrometer test and remote wire line vane test are in very good agreement. The laboratory vane tests are generally less than half of the *in situ* values.

(*c*) *Pressuremeter Test*

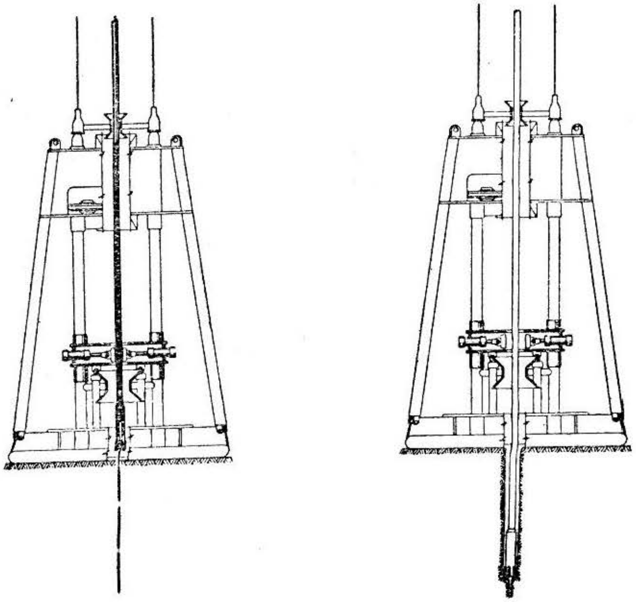
A technique devised by Menard (1960) to measure the soil properties involves the expansion of a cylindrical membrane in a prepared cavity in the soil. The membrane forces the walls of the hole to expand as a result of internal fluid pressure. Both the pressure and corresponding volume changes are measured and plotted. Comparison of the experimental pressure-volume relationship with that of theoretical values enables the determination of material parameters such as elastic modulus and yield strength.

Menard's Pressuremeter has been used in undewater borings for determination of *in situ* strength of sea floor soils. Figure 8 shows the pressuremeter assembly (Gambin 1971) which can be lowered into any hole drilled in advance, or may even be driven in granular soft material. As the reaction forces are obtained from the tested wall themselves, the



(a) Jacking unit on bottom, drill pipe being lowered.

(b) Drill pipe clamped and held 3 ft. off bottom, and wire-line cone penetrometer locked into drill bit 20-ft cone rod attached.



(c) Cone forced to 15-ft. penetration by repeated jack strokes

(d) Cone and rod removed, hole drilled to 14-ft. depth, ready for repeat of cone test cycle.

FIGURE 6 Operation of "Stingray" cone penetrometer system (After Ferguson et al. 1977)

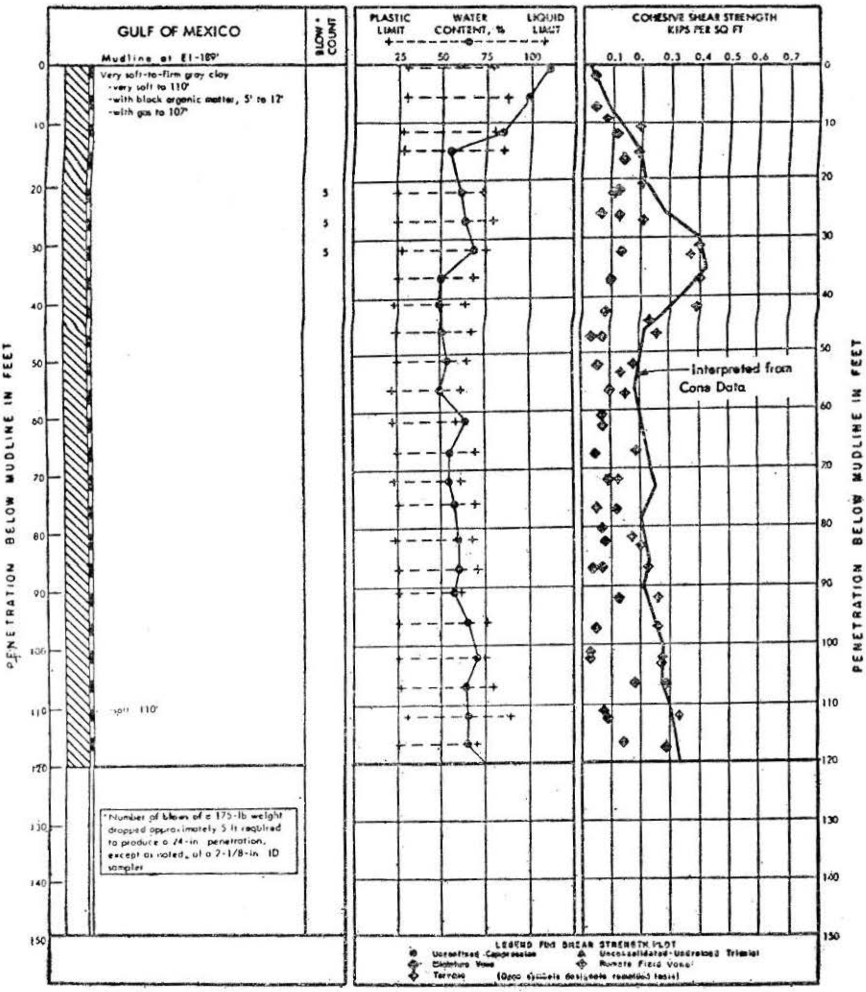


FIGURE 7 Log of boring and "Stingray" cone penetrometer test results (After Forguson et al, 1977)

probe is very light. The reading-out unit stays on board the ship or the barge, and is linked to the probe by specially designed plastic leads. From the site readings a loading curve can be plotted which gives the shear modulus and limit pressure of the tested stratum, Menard (1965) has described the procedures for calculating bearing capacity and settlement from the pressuremeter test results.

This equipment has been used extensively for offshore work, either from a floating craft or from a fixed platform, some at 150 feet (46 meters) below the sea bed in more than 300 feet (91 meters) of water.

Standardization of Testing procedures

Factors that influence the shear strength obtained by a vane shear test have been studied since the test was first proposed and are summarized by

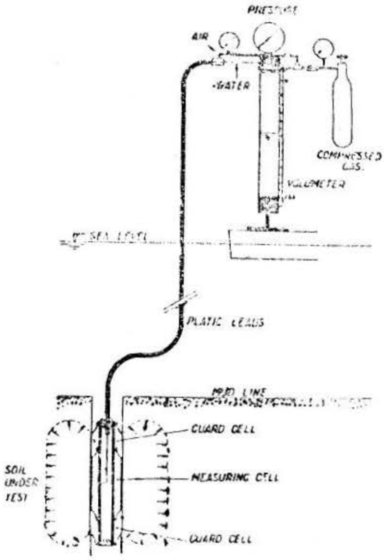


FIGURE 8 Pressuremeter test assembly (After Gambin 1971)

various authors (for example; Cadling and Odenstad 1950, Flaate 1966, Osterberg 1957). One of the principal influencing factors is the effect of the vane rotation rate on the shear strength. While the effect of rotation rate on shear strength was being studied, no one angular speed was established as a standard, although six deg/min has been generally adopted by convention (Osterberg 1957). In 1972 the American Society for Testing and Materials (1974) set six deg/min as the maximum allowable rotation rate for the field testing of terrestrial soils. This standard rate is considered to be too slow for marine *in situ* testing where time conservation is desirable, and therefore a higher rotation rate ranging from 45 to 90 deg/min is being practiced by various groups testing marine soils. Smith and Richards (1975) conducted several laboratory vane tests on cores at rotation rates of 21 and 80 deg/min and found that the higher rotation rate caused generally a 13 percent increase in good quality cores and a 27 percent increase in a core that had a very high carbonate content. Similarly, Dayal and Allen (1975) has shown that the strength profiles for cohesive soils obtained from static penetration tests are highly influenced from the penetration velocity. Although this test has not been standardized formally, a generally accepted practice has been developed. The adopted penetration rate is 0.6 to 0.8 in/sec (1.5 to 2 cm/sec) for terrestrial use (Begemann 1965). However, this speed is considered to be too slow for marine application and, therefore, a high penetration speed is generally used (4 to 5 in./sec; 10 to 13 cm./sec).

In the author's knowledge, there are no standard, formal, or accepted operating and testing procedures available for adaptation to marine work for any of the Geotechnical tests currently being practiced. As can be seen from the previously cited examples, the test results are highly susceptible to testing procedures, especially the testing speed. In order to provide a comparable and meaningful interpretation of data, a rationalized and mutually accepted standardization of testing procedures should be established. Furthermore, there are no standard procedures available for calibration of these instruments which is another important aspect of any testing program. In most cases the calibration of the equipment is conducted in air at ambient temperatures without providing any consideration to actual operating conditions. No comprehensive or intercalibration program exists which can be followed to compare and compensate for sea state. In order to improve the quality, precision, and accuracy of any measurement system, the calibration standard should be established as an integral part of overall standardization of testing procedures.

Indirect Methods

Experimental studies in soil mechanics have indicated that a soil's strength properties can be related to some degree to its density, moisture content, or porosity. Consequently, in certain circumstances the identification of the type of soil present on the ocean floor (sand, clay, and so forth) and the measurement of its density or porosity can lead to estimations of its strength. The density, porosity, and soil type can be obtained indirectly from various kinds of measurements. The commonly used techniques are:

(*a*) Acoustic Sounding

(*b*) Nuclear Method

(*a*) *Acoustic Sounding*

The acoustic method is employed to explore the strata beneath the sea floor to a depth of several hundred feet. The method is based on the fact that the velocity of propagation of a wave or impulse in an elastic body is a function of the modulus of elasticity, the Poisson ratio and the density of material and that very great differences exist between wave velocity in solid rock and loose sedimentary deposit. The elastic wave is produced by underwater energy sourced placed in disturbance free zone. The time required for the impulse to travel from the shot point to various points is determined by a small vibration detector "hydrophone" which transfers the vibrations into electrical currents and transmits them to a recording unit or oscillograph, equipped with a time mechanism.

There are two principal types of acoustic methods of exploration. One method depends on the refraction of the elastic waves between the various strata, and the other utilizes the reflection of the waves at the interfaces betweén the strata.

Refraction Method

Refraction surveys in the ocean began in 1937 on Woods Hole Oceanographic Institution ships. Until recently most refraction surveys carried out in the search for oil have required two ships, one for shooting and the other for receiving signals. The energy source has almost always been dynamite and charges up to many hundreds of pounds have been necessary for receiving usable seismic arrivals at the maximum distance, generally as great as 15 miles (25 kilometers), between the boats. The cost involved in operating two boats and in using such large amounts of explosives has been tended to discourage geophysicists from using refraction survey, even in areas where the kind of information it yields would be highly desirable. Recently a new technique has been developed by Lamont Geological Observatory of Columbia University (Le Pichon and Heirtzler

1968) which requires only one ship and does not make use of dynamite at all. This involves an air gun as energy source and a receiving hydrophone which hangs from a floating sonabuoy transmitting the signals from an antenna to a recorder on board the shooting ship. The sonabuoy is thrown into the water from the ship, which moves away from it along a line. A recording drum is equipped with a mechanism for setting off the air gun signals when the recorder sweeps in a zero position (usually after every ten seconds). This technique has been successfully tried for numerous offshore oil exploration projects.

The seismic refraction method can be used only when the wave velocity is greater in each successive stratum. The presence and thickness of a stratum which transmits the waves at lower velocity than the overlying stratum cannot be determined by this method. In some cases, it has been found that the loose deposited sediments have a lower velocity than water; in such cases the top layer (sediment) velocity is estimated from experience. Complications are occasionally encountered when the wave velocity in the sediment of loose deposits increases gradually with depth. The path of the first impulses and travel-time diagrams will then be curved, and it becomes difficult to determine the actual wave velocities and the thickness of nonuniform strata.

The refraction method is particularly useful for reconnaissance of little explored offshore areas because it yields unique information of a kind that cannot be obtained by any other type of measurement. By refraction one can determine not only the approximate depth and dip but also the velocity of high-speed subsurface markers. Knowing the velocity of rock layers, one can generally estimate whether they are unconsolidated, semiconsolidated, or consolidated even without further identification. Unless there is a massive limestone layer in the sedimentary section, the basement can be mapped by refraction survey and important markers in the sedimentary section can be followed across the area at the same time.

Reflection Method

It is the simplest and least expensive method for marine reconnaissance exploration. The use of a continuous signal profiler to record the repeated discharge of energy at uniform intervals from a non-dynamite source such as Sparker (Beckmann, et al. 1959) or air gun have made it possible to carry the work at the ship speed of 5 to 10 knots (Dorbin 1969). With the aid of multiple receiving points, it is possible to collect the information concerning the depth, type, and dip of strata (Hill 1963).

Reflection records are very effective in the planning and control of dredging operations as the information regarding the amount of material available for movement by dredge and degree of difficulty in dredging is readily available. Seismic record is also very effective when used in conjunction with borings in foundation studies and in locating the potential geological hazards in the region of a possible construction site.

The successful seismic reflection survey is dependent upon both the physical properties of marine soils and underlying bedrock, and on the selection of proper survey instruments and system settings to optimum signal quality. In many areas, the properties of layered sea floor materials do not provide a high acoustic contrast. For example, the unconsolidated clay atop granite bedrock will certainly provide a pronounced reflecting horizon, but the contrast between the loose silty sand on flat lying weathered shale may result in poor reflection or may be indistinguishable on the profiling records. In Hudson Bay, for example, the first session of reflection work yielded results that were so poor that no digital processing was capable of extracting useful information (Hobson 1967) whereas magnetic and refraction methods were quite successful. If the principal problem is to determine the thickness of sedimentary section, this method may not be reliable as the deeper layer may not produce reflection at all.

The equipment selection is an important consideration in acoustic survey because the use of high frequency to improve resolution results in a loss of penetration. Depending upon the soil properties, depths of the order of 1,000 feet to 1,200 feet (305 to 365 meters) can be penetrated with the type of high power spark gap or "sparker" normally used in engineering surveys. The resolution, however, is not likely to be better than about 15 feet (457 cm.) and hence is not sufficiently accurate for evaluation of critical soil zones immediately below the seabed. High resolution profilers such as "boomers" or multielectrode sparkers give greater resolution and therefore more detail of the upper layer but with much reduced penetration. The boomer gives greater resolution than the multielectrode sparker but can only be used in the calm sea states, and so has limited use in hostile sea operations.

Proper interpretation of the acoustic measurements requires data on sound velocities in different soil and rock layers. During the last two decades, extensive studies have been carried out to measure sound velocities in laboratories and *in situ* to establish the relationships between porosity, density, and mean grain size of the material. Based on the measurement of sound velocity on similar materials occurring on shelf and slope, abyssal plains, and abyssal hills of the Pacific Ocean, Hamilton (1970) has concluded that the sound velocity in a particular type of sediment is independent of the elevation, location, and water depth. As more experience is gained in this field and with the dissemination of information available on the acoustic properties of soils, the state of the art of interpretation of acoustic data will be improved.

(*b*) *Nuclear Method*

The *in situ* bulk density and water content of sediments are measured by gamma radiations and neutron radiations, respectively (Keller 1965, Lai, et al. 1968, Meigh and Skipp 1960, Preiss 1968). In gamma ray method the number of electrons present in each cubic centimeter of sediment is measured and related to bulk density of sediment. In neutron radiation, the number of hydrogen nuclei present in each cubic centimeter of sediment is measured and expressed in grams of water per cubic centimeter. In the nuclear method, the accuracy required from an instrument is an important design criterion. If readings accurate to five per cent are required, design, construction, and calibration are simple. If, however, an accuracy of one per cent or better is required, design of the system and choice of the calibration specimens require much time and effort.

In the North Sea development, radioactive logging technique was experimented for deep drilling to obtain continuous interpretation of the soil stratification, *in situ* density, and water content (Ruiter and Fox 1975). The tool had a diameter of 1.6 inches (40 mm) and logging was carried out in upward direction inside the drill pipe, after completion of the hole. A wave compensating system prevented reversals of direction due to motion of the vessel. The measurements included a natural gamma ray log for clay content, and neutron-gamma and neutron-neutron for density and porosity.

The lithology obtained from the natural gamma ray log indicated that no significant soil layers had been missed out in the boring profiles. The calibration for determination of density and porosity was difficult and time consuming due to the unknown effects of the surrounding drill pipe, of the irregularly shaped hole and possible eccentricity of the drill pipe in the hole.

Summary and Conclusions

It is recognized that currently available underwater soil sampling techniques provide a disturbed sample for laboratory analysis, especially for shear strength testing which is a useful parameter in designing and assessing the behavior of offshore structures. Test results have indicated that the ratio of *in situ* vane to laboratory vane strengths varies from one to more than three. Hence, measurement of the soil strength properties *in situ* is suggested as a means of enhancing data quality. Available significant information concerning the recent trends in underwater *in situ* soil testing has been summarized.

There are a number of underwater activities such as pipeline projects, cable installation, harbor dredging, and light underwater installations, which require investigation of the properties of nearsurface deposits only. Among the shallow penetration *in situ* testing tools available, free falling type of dynamic penetrometer, and submersible platforms equipped with a cone penetrometer or vane testing device (such as DOTIPOS) show greatest promise.

Most offshore engineering projects require the exploration of sea floor to penetration depths well below the upper 50 feet (15 meters). The land-based *in situ* testing techniques have been discontinued due to cost considerations, since use of these techniques requires either a fixed platform or a calm sea. New, *in situ* testing techniques adapting with the conventional testing procedures from floating vessels have been devised in response to current needs of industry and constitute the most important advance in marine site investigation technology in recent years. One of the new techniques utilizes the wire line system for conducting remote vane or cone penetrometer tests. Another recent development is submersible platform type of cone penetrometer "Seacalf".

Each of the direct methods described has or will have its place in meeting needs for deep-penetration *in situ* testing below the ocean floor. Eact method also has its limitations—either physical capacity, suitability, availability, or economic feasibility. For example, the vane shear test is not applicable to sand and inorganic silt. The pressure meter is to be used in a cased borehole. The cone penetrometer test does not yield any soil sample for physical identification and other laboratory tests. The penetration capacity of submersible platform type of penetrometer is limited by the available thrust capacity of the rig. The selection of any one of these methods should be based on site and project requirements.

Currently there are no standards for operating, testing, and calibration procedures for any of the underwater *in situ* soil tests. It has been shown that data are highly influenced by the testing procedures, and as such, a rationalized and mutually accepted standard should be established for testing and calibration procedures for each test in order to provide quality data for comparison and meaningful interpretation.

Acoustic profiling is a means for accurately and rapidly mapping general subsurface characteristics over a large underwater area provided it is supplemented by boring and sampling. Acoustic records provide information about the altitude and configuration of the shallow and deep sediments, as well as gas seeps, gas-charged zones, faults, bedrock, buried river channels, pipelines, and other hazards. Side-scan sonar observations can be combined with acoustic profiling to provide a three-dimensional representation of subsurface conditions. These data are a vital base for submarine foundation assessment, providing assurance that lateral variations in the submarine soil profile are adequately sampled, and that the selected foundation horizon is continuous. Knowledgeable interpretation of such data yields valuable information on the mode of formation and post depositional history of the strata. A well-designed marine geophysical investigation often can be used as a basis for reducing the density of submarine borings and *in situ* testing. The savings in drilling costs commonly more than offset the expense of the geophysical program.

In conclusion, there are three primary mothods for collecting geotechnical information from an offshore site, namely: interpretation of acoustic records; sampling and laboratory testing; and *in situ* testing. Each method has its own particular advantages and limitations and it is usually best to employ all three methods and correlate the results to gain optimum information return.

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