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EXPENDABLE DOPPLER PENETROMETER: INTERIM REPORT

By

R. M. Beard

April 1976

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An expendable penetrometer using the Doppler principle has been developed to expediently test seafloor soils at water depths to 20,000 feet. The velocity of the penetrometer is measured as it penetrates seafloor soils; from the velocity record, soil penetrability and an estimate of soil strength are available. The penetrometer weighs 365 pounds, is 10 feet long, is 3-1/2 inches in diameter, and is easily deployed from a ship. Initial testing indicates that the concept of a Doppler instrumentation system is workable, that penetration can be

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1. Doppler Effect Instrumentation I. YF52.556.999.01.102

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CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

This report describes the development of a dynamic penetrometer for testing seafloor sediments at water depths to 20,000 feet. The work was funded by the Naval Facilities Engineering Command. The purpose in developing this tool was to provide an expedient means to determine seafloor characteristics and properties relevant to site selection for and design of direct embedment anchors. This tool has several intended and potential applications.

For noncritical embedment anchor installations the penetrometer can probably be used by itself to select the fluke size to be used (most embedment anchors have several fluke sizes or types to accommodate a variety of seafloors). This can be done based on the penetration depth of the penetrometer. Experience will be required, but in general shallow penetration would indicate using a small fluke and deep penetration would indicate using a large fluke. Fine grained soils that are approximately normally consolidated in the upper 50 feet of sediment (defined as having a surface shear strength less than one pound per square inch) cover about 30 percent of the seafloor. In these soils it is anticipated that the penetrometer can provide sufficiently accurate soil strength data to determine the short-term holding capacity of an embedment anchorage. Because the short-term capacity will govern in these soils (Beard and Lee, 1975, and Yen, 1975) this capacity is the design capacity. For other soils where the long-term capacity will govern this is not possible because the penetrometer cannot measure the soil density and friction angle required to estimate the long-term capacity.

One use of the penetrometer will be to supplement coring and geophysical measurements. Penetrometer data gathered intermittently between cores will allow interpolation between cores of strength measurements made on the cored soil. This information could otherwise be acquired only with additional coring, which is several times more time-consuming and costly than performing penetrometer tests.

For final site selection it is necessary to determine the homogeneity of the proposed anchor location. Anomalous conditions, such as small submarine lava flows and ice-rafted detritus at selected sites, are of concern because they can prevent proper embedment anchor performance. Multiple penetrometer tests will help determine the probability of occurrence of anomalous conditions and therefore help to estimate the site's homogeneity.

The penetrometer would also be valuable in helping to determine the fluke angle to use on a conventional drag anchor with adjustable flukes. The fluke angle is changed to maximize anchor holding capacity in soft and firm seafloors. The penetrometer should easily detect whether the seafloor is soft or firm.

There were two main development goals: (1) to obtain data to a soil depth at least as large as the depth required to achieve the rated holding capacity of the Civil Engineering Laboratory (CEL) 20K anchor (30 feet in clay, 15 feet in sand), and (2) to keep the cost low enough that the tool could be considered expendable, thus maximizing operational flexibility.

Background

The Civil Engineering Laboratory conducted a study and made tentative recommendations for conducting deep ocean site surveys for anchor installations, Rocker, et al., 1972. A tentative plan called for soil coring and acoustic subbottom profiling to be the mainstays in providing the information required to site and design anchors. They saw soil strength, penetrability, and thickness, and the occurrence of anamolous conditions (e.g., ice-rafted detritus and small submarine lava flows) as important parameters to determine. One of the conclusions in this report was that the development of simplified in-situ testing equipment would significantly improve the chances of conducting successful site investigations. Rocker recommended that an expendable penetrometer be developed to provide an improved site-investigation capability.

An additional study of the most suitable technique and equipment to provide the required seafloor data was made by Rocker and Raecke (1972). After studying a wide range of existing and conceptual survey tools, they concluded that a gravity, penetrating, test anchor* was the best tool for acquiring data to design direct-embedment anchors. They also recognized that a dynamic penetrometer was the only truly expedient tool, the easiest and the least costly to use, and, therefore, the most attractive tool if satisfactory data could be acquired from it. Therefore, they recommended that a gravity, penetrating, test anchor be developed and that investigation into the possible development of a dynamic penetrometer continue.

Work was initiated to develop a penetrating test anchor. A hydrodynamic model study was conducted to determine drag coefficients and the stability of several concepts. Penetration studies with the same models were also conducted. It was determined that to achieve required performance a gravity, penetrating, test anchor would weigh about 3,000 pounds and be about 20 feet long. Several disadvantages in the development of such an anchor were noted: (1) it would be difficult to use a device of this size; (2) use would be limited to weather conditions favorable for coring; (3) the time required to perform a test would be as lengthy as that necessary for coring, and therefore the number of tests would be limited; and (4) the extended onsite time would jeopardize the security of a site. Therefore, it was decided that a re-evaluation of its usefulness was in order. The result of the re-evaluation was a recommendation to stop development of a gravity, penetrating, test anchor and to begin development of an expendable penetrometer. It was thought that an expendable penetrometer could expediently meet any operational requirement, provide knowledge about lateral soil variability when compared to sediment core data, provide knowledge about anomalous conditions (dependent upon the number of tests), and give an indication of soil penetrability and strength.

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* In concept only, the gravity penetrating test anchor was never developed.

Others have worked on seafloor penetrometers. Sandia Laboratories began development of one in 1970 (Colp, et al., 1975) and Scott (1970) reported on a mechanical accelerometer for use with an ocean penetrometer. Delco Electronics developed an expendable soil bearing meter for use in the ocean that was similar to an expendable bathythermograph (Robertson, 1965). None of these devices was found suitable for the intended use of the expendable penetrometer proposed. Their sizes are too small for the penetration required, and they are not operable to the required water depth. A new approach to obtain the necessary penetration and to function at water depths to 20,000 feet was necessary.

Approach and Scope

The development of an expendable penetrometer involved design of two components: a vehicle to transport an instrument to and into the seafloor and an instrument to gather data as the vehicle penetrated into the seafloor. In each of these designs, cost played an important role because the penetrometer was to be expendable. Design of the vehicle was based on theories of hydrodynamics and soil penetration to obtain a size and shape consistent with operational goals. Design of the instrument system was primarily concerned with conceiving the best instrument for gathering data about the vehicle as it penetrated the seafloor and getting the data back to the surface vessel.

This report provides a description of the expendable penetrometer, presents its theory of operation, outlines the process of its development, and documents the results of initial testing. Also presented are discussions of data quality, factors that can affect the data, and plans for additional testing and evaluation.

DESCRIPTION OF EQUIPMENT

The tool developed – the Expendable Doppler Penetrometer – utilizes the Doppler principle: a sound source moves in relation to the receiver of the sound emitted. Thus, the velocity of the penetrometer can be measured. The penetrometer consists of two components (Figure 1): (1) a heavy, hydrodynamic, shaped vehicle for speeding the penetrometer to the seafloor and providing the impetus to penetrate the soil, and (2) an accurately controlled sound source system for data measurement.

The vehicle is a lead-filled, 8-foot-long, 3-1/2-inch-outside-diameter pipe. A steel hemisphere is welded to the lower end of the pipe forming an efficient hydrodynamic nose. Welded to the upper end of the pipe is a circular steel plate with a center stud for attaching the sound source system. Three equally spaced fins are attached to the pipe at the upper end to provide stability for the falling penetrometer. The total weight of the vehicle is about 355 pounds.

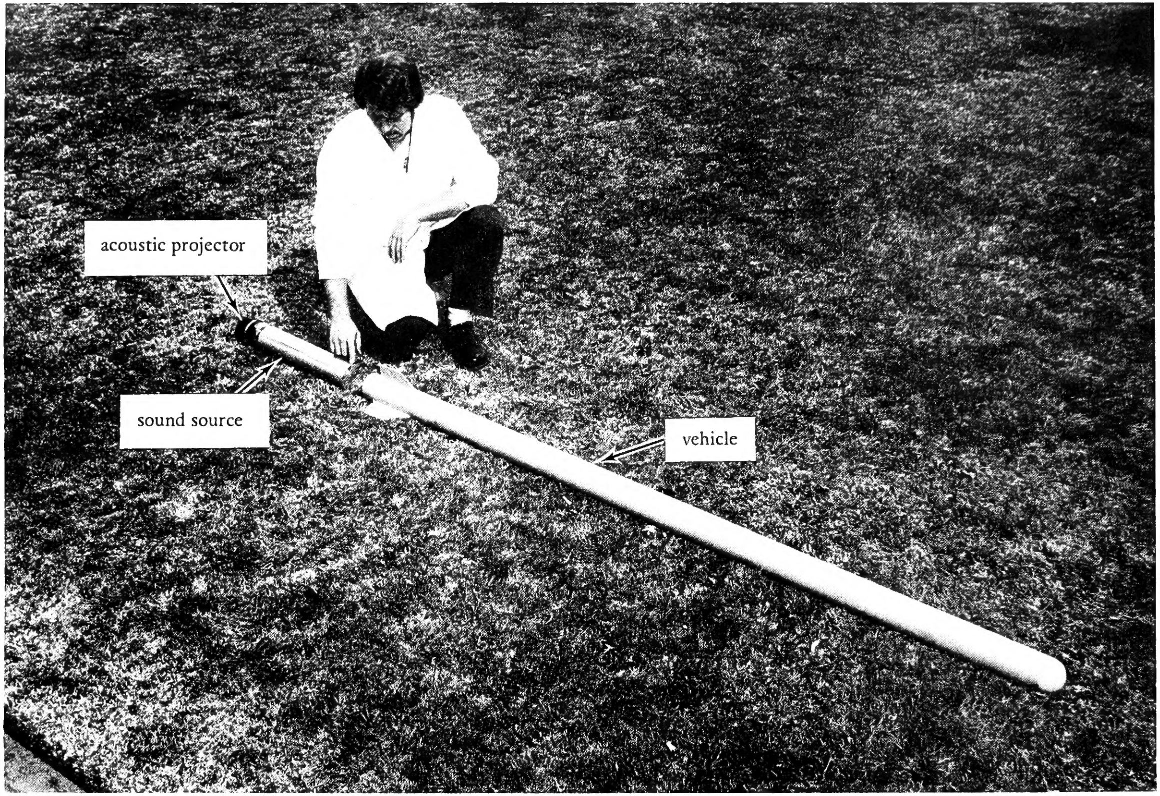

Figure 1. View of Expendable Doppler Penetrometer.

The sound source system consists of an acoustic projector, a power supply, electronic circuitry, and a pressure-resistant housing. The power supply and electronic circuitry are contained in the pressure-resistant housing and the acoustic projector is attached to the top of this housing. This package weighs about 10 pounds and is 23 inches long and 3-1/2 inches in diameter. It is designed to screw onto the stud at the upper end of the penetrometer vehicle.

When the vehicle and the sound source are assembled, the Expendable Doppler Penetrometer is a 365-pound, 10-foot-long, 3-1/2-inch-diameter package (see Figure 1). The penetrometer attains a free-fall terminal velocity of about 80 feet per second and should penetrate up to 30 feet into soft seafloor soils. Less penetration is expected in firm soils and sands. While it is falling, it emits a 12,500-Hertz sound held to an accuracy of plus or minus one part in 100,000. It is this sound that is received with shipboard equipment as a Doppler-shifted signal that becomes the data from the penetrometer.

THEORY OF OPERATION

The Doppler principle can be stated as

$$f' = f \frac{v}{v + v_s} \tag{1}$$

where

f' = frequency received
f = frequency transmitted
v = velocity of sound
v_s = velocity of source (penetrometer)

This principle is used by the Expendable Doppler Penetrometer to generate an analog of the kinematics of its motion. The depth sounder-receiver, with which most Navy ships are equipped, may be used in the listen mode to receive the signal from the penetrometer. At the expected terminal velocity of the penetrometer (about 80 feet per second) and its prototype operation frequency of 12,500 Hertz, a sound at 12,304 Hertz will be received by the depth sounder-receiver. This is a frequency shift of 196 Hertz or 1.63% from the 12,500-Hertz signal of the penetrometer (assuming the velocity of sound in seawater is 4,800 feet per second). In the range of penetrometer velocities of 0 to 100 feet per second it can be shown that the frequency shift is nearly linear at 2.45 Hertz for each foot-per-second of velocity. The changes in the received frequency are then a linear frequency analog of the kinematics of the penetrometer. This frequency analog may be recorded and processed as is any frequency-modulated telemetry signal.

The processing is initiated in the depth sounder-receiver where the signal is shifted, by heterodyne methods, to a lower frequency range. The audio output of the depth sounder-receiver in this lower frequency range is then processed by a frequency-modulated tunable discriminator into a direct-current voltage. This voltage from the discriminator can then be recorded on an instrumentation recorder together with Inter Range Instrumentation Group B time. This recording is, as is the Doppler shifted signal, an analog of the kinematics of the penetrometer.

This recording can then be processed to obtain the depth of penetration and the velocities and decelerations of the penetrometer as it entered the soil.

DATA ACQUIRED

Data from the Expendable Doppler Penetrometer is expected to provide information on soil strength and penetrability and the occurrence of anomalous conditions. In addition, the penetrometer data can be used to extrapolate data between widely spaced cores.

From the velocity data, deceleration can be obtained by differentiating the curve of velocity versus time. This deceleration can be translated into a deceleration versus depth curve. Deceleration at a point is indicative of strength at a point. However, point data is not available from the penetrometer because its length tends to average data. Nevertheless, changes in strength are apparent as the deceleration changes; hence, the type of strength profile can be determined. Examples would be uniform strength with depth, uniformly increasing strength with depth, or soils with layers of different strength. An estimate of the magnitude of strength with depth would also be available. The ‘‘averaging’’ of the penetrometer will mask changes if the layers are thin (say 3 feet thick or less) or if the strength changes from layer to layer are not significant.

Penetrability is a general term to indicate relatively how easy or difficult a seafloor would be to penetrate for a given penetrator. For example, rock would be considered impenetrable for blunt, slow-moving objects, and would have very low penetrability for a specially designed ballistic anchor projectile. Soft clays, on the other hand, would have high penetrability for a ballistically embedded anchor projectile. The penetrometer should be a good tool for estimating relative penetrability because it penetrates the seafloor during a test. Correlation with anchor penetration data will enhance penetrability estimates.

Data from the penetrometer can also be used to extrapolate between widely separated core data. Often, when site surveys are conducted cores are separated by distances of tens of miles and sometimes by hundreds of miles. The gap between cores can be filled in with penetrometer data. By performance of penetrometer tests near the cores and at intervals between the cores, the core data can be extrapolated based on similarities and differences observed in the penetrometer data. Changes in the strength profile and the location of layer interfaces should be detectable. Acoustic techniques can also detect layering if the soil density increases significantly from layer to layer with increasing depth. However, acoustics cannot detect layers if the soil density decreases with depth.

The penetrometer will be of value in determining the occurrence of anomalous conditions. At selected anchorage sites multiple penetrometer tests will help assess the probability of occurrence of small submarine lava flows and ice-rafted detritus. The extent of ‘‘pavement’’ formations, extremely soft sediments, and layered sediments can also be determined with multiple penetrometer tests. Lava flows and detritus will be apparent from a lack of penetration (surface formation) or abruptly interrupted penetration (subsurface formation). The other conditions will require interpretation of the data record, but the records are expected to be quite different from those of normal soil formations.

PENETROMETER DESIGN

Vehicle Development

The shape and weight of the vehicle were to allow penetration of 30+ feet into typical deep ocean clay soil deposits and yet were to maintain low cost. Lowest cost for the vehicle was considered to be synonomous with minimum size, simple shape, and ease of fabrication. The design process involved a parametric study with a wide range of sizes of solid steel and lead-filled pipe vehicles. Performing the parametric study required determining penetration and terminal velocity of each shape considered.

Penetrations were calculated using a simplified form of that presented by Migliore and Lee (1971). In this method the initial kinetic energy of the penetrating object is depleted by the work done as the object penetrates into the seafloor. Calculations were performed on an incremental basis. That is, work done over short distances was subtracted from the kinetic energy of the penetrator until its kinetic energy was dissipated. Mathematically,

$$\Delta KE = \left| N_c A_f c + A_s c \right| \Delta d \qquad (2)$$

where ΔKE = work done

N_c = bearing capacity factor (10)

A_f = frontal area of object

c = soil cohesion

A_s = side area of object

Δ_d = depth increment

The procedure has been compared to the results of a series of model dynamic penetration tests performed in a mud flat on San Francisco Bay near Mare Island (Figure 2). The test models in three sizes were configured similar to the penetrometer; they attained impact velocities ranging from about 70 to 90 feet per second. The figure shows that the penetration prediction method gives reasonable estimates of penetration for long cylindrical objects entering the soil with their axis vertical.

Terminal velocities were obtained from standard hydrodynamic equations. The drag coefficient used for all the penetrometers in the parametric study was 0.5 as determined by the Naval Surface Weapons Center, White Oak, from model studies in their 100-foot-deep test tank as reported by Waser (1973). This drag coefficient should have been adjusted as the length-to-diameter ratio of the penetrometer was changed. However, for initial results this was deemed unnecessary because it was not expected to vary significantly over the range of penetrometer sizes being studied. Later, when the limits of the size of the penetrometer had been narrowed, drag was separated into a frictional component on the side and a pressure component on the nose and base to obtain more accurate estimates of terminal velocities and resulting penetration.

The initial calculations were made for three soil profiles: a red clay, a calcareous ooze, and a terrigenous clay. Penetration trends were consistent from soil to soil. Therefore, when the study's limits were narrowed, penetrations were calculated in only one soil, a pelagic clay.

The parametric study showed that steel-shafted penetrometers were about half as efficient as lead-filled steel pipe penetrometers (a steel-shafted penetrometer equal in size to a lead-filled one would penetrate about half as far). For this reason lead-filled steel pipe vehicles were chosen for the penetrometer.

Other data from the initial parametric study were that the optimum vehicle size was between 200 and 500 pounds with a diameter between 2 and 4 inches. This size range of penetrometers was then studied in greater detail. In this continued parametric study, friction and pressure drag were considered separately so that improved hydrodynamic drag coefficients could be utilized. Standard pipe sizes were used. A plot of penetrations into a pelagic clay versus pipe diameter is shown in Figure 3 for penetrometers of equal weight and equal length. A 10-pound instrument package of constant volume was attached to each of the hypothetical penetrometers.

Figure 3 shows that for a given penetrometer weight that penetration will be nearly constant over the range of penetrometer diameters being considered. Therefore, length and other factors govern the design selection. With 35 feet of penetration in a pelagic clay as a target, the weight of the penetrometer should be about 350 pounds. At this stage the instrumentation design had progressed to hardware component selection. A trade-off between vehicle diameter and the diameter of an acoustic projector resulted in the selection of 3.5 inches as the diameter of the penetrometer. Therefore, the penetrometer would be 10 feet long, weigh about 365 pounds, and be 3.5 inches in diameter. The vehicle would compose the lower 8 feet of the penetrometer and weigh 355 pounds.

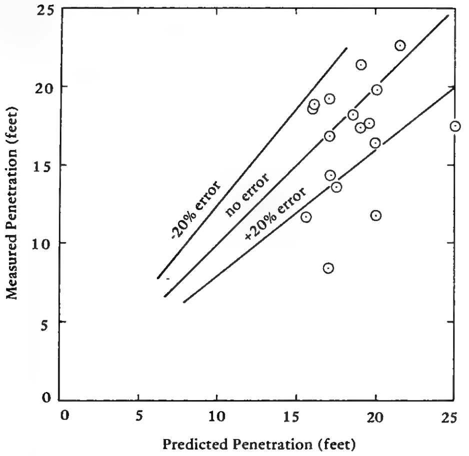

Figure 2.
Comparison of measured and predicted penetrations at Mare Island for all shapes and configurations.

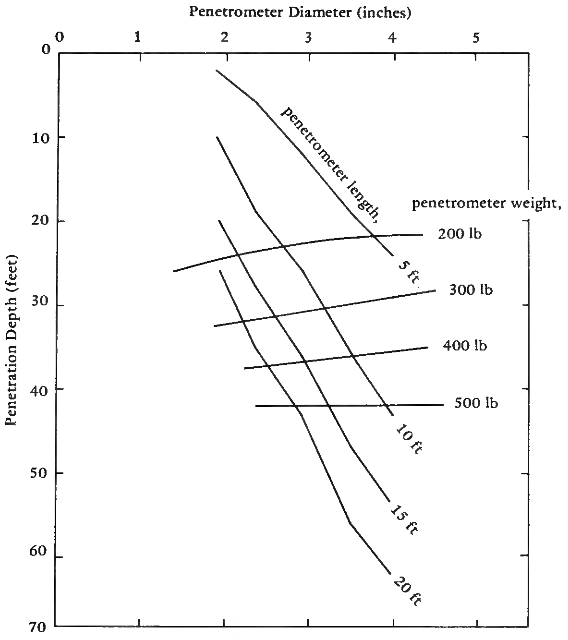

Figure 3. Penetration depth in a pelagic clay versus penetrometer diameter for pentrometers of equal weight and penetrometers of equal length.

Stability of the penetrometer was obtained by having the center of gravity 8.5% of the body length below the center of buoyancy and by having fins 8 feet up from the nose. The fins aid stability in two ways: first, by providing a righting moment when the penetrometer deviates from the vertical and, second, by helping to break up vortices that may tend to form in the wake of the penetrometer.

A hemisphere was chosen for the nose shape because it offered minimum drag (Hoerner, 1965) and a relatively easy-to-manufacture shape.

Instrumentation Development

Initial work on instrument concepts centered on the use of accelerometers to measure the dynamics of the penetrometer. Two methods of transmitting the accelerometer data to the water surface were investigated. One method involved using a wire-link (similar to expendable bathythermograph wire-links); the other, acoustic transmission.

In the use of wire-links two problems were encountered: first, the electrical performance of the cable was found to be undesirable for the purpose and, second, the design payout rate of the wire was only one-fifth the payout rate required. Considerable engineering development would have been required to overcome these problems. Therefore, the use of expendable wire-links was not considered further.

Acoustic transmission where the frequency of an acoustic projector varied according to deceleration of the penetrometer was determined to be feasible. The cost of such a system, however, appeared to be high because of the number of components required: an accelerometer, a signal conditioner, a power supply, amplifiers, and an acoustic projector. Another problem with this system was that the required range of operational frequency of the acoustic projector was very wide to achieve a high signal-to-noise ratio. Considerable noise came from Doppler frequency shifts caused by the change in the velocity of the penetrometer relative to the listening device as the penetrometer entered the seafloor.

An alternative to both of these potential instrumentation systems was to utilize the Doppler shift of a constant frequency sound source on the penetrometer to determine the velocity of the penetrometer as it penetrated into the seafloor. The advantages of an instrumentation system utilizing the Doppler principle were that no trailing wire was required and that cost would be significantly less than the other concepts studied.

A prototype sound source was designed and fabricated. It consisted of an acoustic projector, a power supply, and electronic circuitry to control the frequency of the projector to an accuracy of plus or minus one part in 100,000. The housing was an aluminum cylinder. A vacuum test point for checking the O-ring seals was placed in the base of the housing. The instrument was designed to turn on when it entered the seawater by using the seawater to complete a starting circuit.

Design of the sound source centered on the amount of acoustic output required to send the signal through at least 20 feet of sediment (30+ feet of penetration minus the 10-foot penetrometer length) and 20,000 feet of water and to have a usable signal at the water surface. This design required consideration of acoustic losses in the transmission mediums, the acoustic characteristics of the sound source, and the acoustic characteristics of the listening system at the ship.

Expected transmission losses for 30 feet of penetration and 20,000 feet of water are:

Sediment attenuation loss	20 decibels (db)
Seawater attenuation loss	+16 db
Spreading loss for 20,000 feet	+76.5 db
Total Losses	112.5 db

20log R (m)
20·[~~4~~.3.7]

All of these values are pressure levels referenced to 1 μbar at 1 yard. The sediment loss was calculated after Hamilton's (1972) data, and the spreading and water attenuation are those given by Horton (1959).

The required sound pressure level at the receiving hydrophone can be calculated from the required signal at the receiver and the sensitivity of the hydrophone. The signal required at the receiver of the depth sounder-receiver is 20 μV which can be translated to -94 dbV. The sensitivity of the hydrophone of the depth sounder-receiver is about -75 db referenced to 1 volt at 1 μbar of pressure. The sensitivity of the hydrophone can be subtracted from the required signal level at the receiver to determine the sound pressure level required at the hydrophone.

Required signal level	-94 db (20 μV)
Hydrophone sensitivity	-75 dbV
Sound pressure level required referenced to 1 μbar	-19 db

Knowing the transmission losses and the sound pressure level required at the receiving hydrophone allows the required source level of the acoustic projector on the penetrometer to be calculated. Since the hydrophone can detect a pressure 19 db below the reference pressure 1 μbar at 1 yard, and since the losses are equal to 112.5 db referenced to 1 μbar at 1 yard, these values can be added to determine the source pressure level. The source pressure level is then 93.5 db above 1 μbar at 1 yard for a nondirectional source. However, the directivity index of the projector, which is related to its beam width, will increase the pressure on the axis of the main lobe when compared to a nondirectional source. Assuming a directivity index of nine, the required pressure level is 84.5 db referenced to 1 μbar at 1 yard.

For the prototype sound sources built at CEL, on-hand acoustic projectors were used. Their acoustic output was insufficient for operation to a water depth greater than several thousand feet.

Another factor that enters into acoustic design is the minimum detectable signal (MDS). MDS is a function of the ambient noise level, the band width of the receiving system, the directivity index of the hydrophone, and the recognition differential between the signal and the ambient noise. This function is expressed in decibel terminology as:

$$\mathrm{MDS} = N_s + 10 \log \mathrm{BW} - \mathrm{DI} + \mathrm{RD} \tag{3}$$

where N_s = spectrum or ambient noise level in decibels referred to 1 μbar
BW = bandwidth, cycles
DI = directivity index, db
RD = recognition differential, db

If the MDS is higher than the source pressure level at the hydrophone, the signal cannot be detected. Conversely, if the MDS is lower than the source pressure level at the hydrophone, the signal can be detected.

To solve Equation 3 the factors in the right-hand side must be determined. First, an assumption needs to be made about RD between the signal and the ambient noise. In acoustic signal processing an RD of 20 db is often used. This RD provides a conservative factor of safety because the signal has an amplitude 10 times the noise. The characteristics of the receiver-hydrophone system are usually known. For the depth sounder-receiver hydrophone on the standard ship, BW is 1,000 cycles and DI is about 15 db (60-degree beam width). The ambient noise level is a function of many different factors that are difficult to separate. Myers, Holm, and McAllister (1969) provide a chart of noise level for different conditions at sea which include rain, wind force (sea-state), ship noise, and other factors in relation to specific frequencies. At the operational frequency of the penetrometer (12.5 kHz) this chart gives the ambient noise as -53 db referenced to 1 μbar at sea state 4, which is a likely maximum operable sea state for using the penetrometer with presently available launching systems. Using these numbers in Equation 3 gives an MDS of -18 db referenced 1 μbar.

Referring to the sound pressure level required at the hydrophone (-19 db referenced to 1 μbar) it is apparent that the minimum detectable signal of the receiver-hydrophone is about the same as the required sound pressure level. If all necessary assumptions are reasonable, providing an acoustic source with a pressure level 84.5 db above 1 μbar at 1 yard and a projector DI of 9 db is adequate.

It is anticipated that development of the penetrometer will include launching systems so that the penetrometer can be deployed at sea state 4 and above. With deployment at an upper sea state 6 (average wave height = 11 feet, average tenth highest wave = 23 feet) as a goal, ambient noise levels will increase by 8 db. Therefore, an equal improvement in the pressure level of the acoustic source or hydrophone-receiver system would be required to detect the signal. An 8-db improvement would be relatively easy to achieve in the receiver-hydrophone alone by increasing the sensitivity of the hydrophone and narrowing the bandwidth of the receiver. The object of any improvement would be to keep the MDS lower than the required source pressure level at the hydrophone.

TEST PROGRAM AND PROCEDURES

Initial testing of the Expendable Doppler Penetrometer was conducted to demonstrate that the concept was workable and that accurate data could be obtained and to discover if the velocity and penetration performance of the device were as expected. To provide required data, tests were attempted at four locations in the Santa Barbara Channel off the California coast in about 100, 600, 1,200 and 70 feet of water.

In all the tests, except one attempted in 1,200 feet of water, the penetrometer was deployed with an intent to recover it. In 100 feet of water this involved lowering a large loop of recovery line in the water and releasing the penetrometer from the water's surface with the free end of the recovery line attached to the rear of the penetrometer. In 600 feet of water, the penetrometer was rigged in a manner identical to a gravity corer. In 70 feet of water it was released at the water's surface and allowed to freefall to the seafloor with only a small cord attached to it. After divers found the penetrometer by swimming down the cord they attached a recovery line. In the test attempted in 1,200 feet of water the penetrometer was released at the water's surface with no lines attached.

In all the tests the CEL warping tug's UQN Sonar Sounding Set was used in its passive listening mode to monitor the penetrometer. After the datum signal was processed through a frequency modulated discriminator the DC-voltage analog of the velocity of the penetrometer was recorded on both magnetic tape and paper for later data reduction.

TEST RESULTS

The first series of tests was conducted in 100 feet of water 2 miles south of Port Hueneme, California, from the CEL warping tug. The loop-of-line technique was used to recover the penetrometer. Four tests were conducted. Because the depth sounder-receiver was not working correctly, the data gathered were not of good quality (see Figure 4). However, it was possible to detect impact with the seafloor when the penetrometer stopped and to estimate impact velocity. This was sufficient to calculate penetrations. Penetrations measured from mudlines on the penetrometer and penetrations calculated from the data compared reasonably well and are shown in Table 1.

The second series of tests was attempted in 600 and 1,200 feet of water about 5 miles south of Santa Barbara, California, from the CEL warping tug. In 600 feet of water the penetrometer was lowered toward the seafloor, rigged identical to a gravity corer. Two tests were attempted, and during each test the penetrometer was prematurely triggered hundreds of feet above the seafloor. On the first test the penetrometer was arrested by the recovery line and returned to the tug. On the second test it snapped the recovery line and was lost. It has been hypothesized that uneven cable payout or the heaving of the tug caused the premature triggering. In 1,200 feet of water, a penetrometer was cast free at the water's surface to freefall to the seafloor with no lines attached to impede its progress. The signal from the sound source was lost after the penetrometer reached a depth of about 450 feet. The penetrometer seemed to be approaching a terminal velocity of about 80 feet per second. It has been hypothesized that the signal was lost because the acoustic output of the sound source reached its limit of overcoming ambient noise and range distance. A calculation error caused the acoustic output to be set too low.

Table 1. Comparison of Field-Measured Penetrations to Penetrations Calculated From Data Taken in 100 Feet of Water

Test No.	Measured Penetration, P_m (inch)	Calculated Penetration, P_c (inch)	P_m/P_c
1	33	30.0	1.10
2	30	27.6	1.09
3	30	26.4	1.14
4	30	26.4	1.14

The third series of tests was conducted from the CEL LCM-8 about 1 mile south of Port Hueneme in 70 feet of water. For these tests the penetrometer was released at the water's surface and allowed to freefall to the seafloor with only a small cord attached to it. This facilitated location of the penetrometer by divers so they could mark the penetration and attach a recovery line. Four tests were conducted. Data gathered were of very good quality (Figure 5). Penetrations measured on the body of the penetrometer and penetrations calculated from the data compared excellently for two tests and reasonably well for the other two tests; the comparisons are shown in Table 2. Penetrations were shallow because the penetrometer was impacting at only 40 feet per second and because the soil was a dense sand. Penetrations ranged from 2 to 3.5 feet. In Figure 5 it is easy to identify changes in slope of the velocity trace which are indicative of changes in deceleration. This, in turn, means that an observable change in resistance took place. This change is due to both increased soil strength and the fact that more penetrometer in the ground means more resistance. However, because of the shallow penetration, it was not possible to separate these two effects.

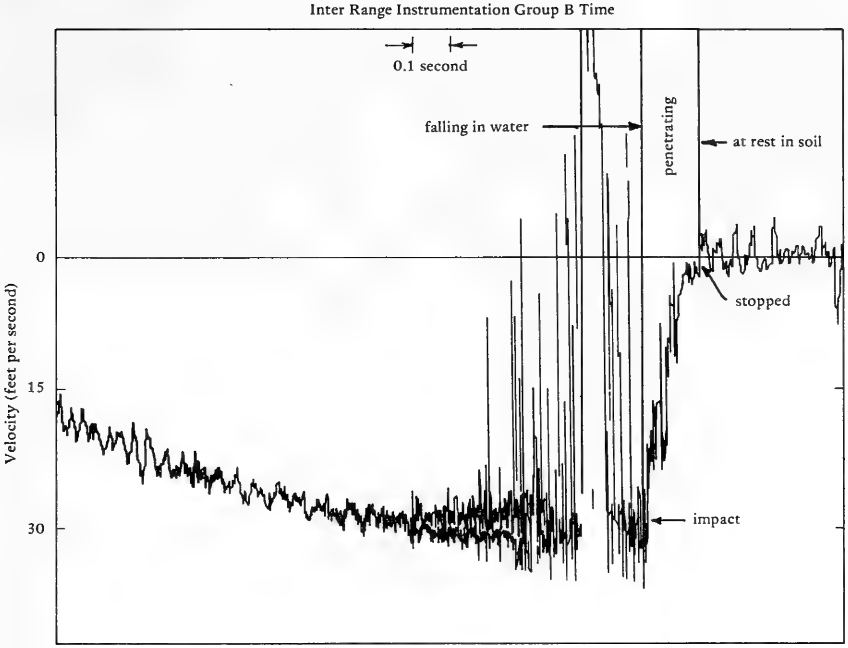

Figure 4. Typical poor trace of velocity versus time from first test performed in 100 feet of water in November 1974.

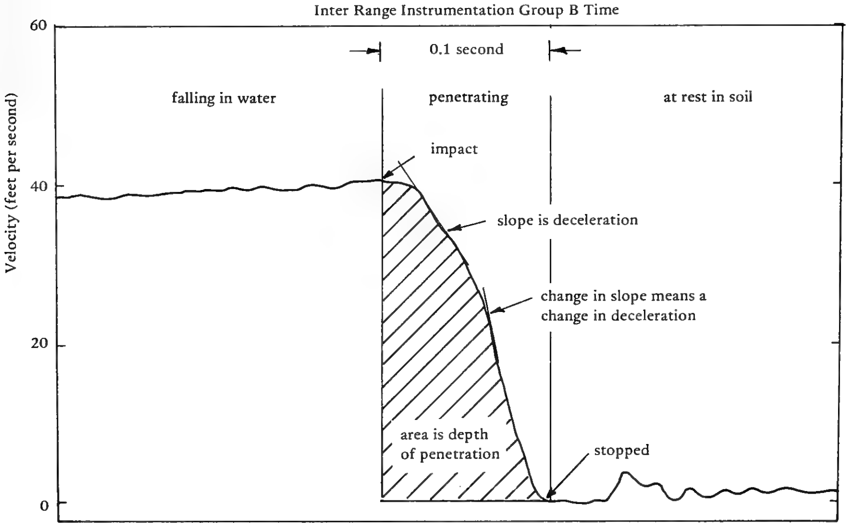

Figure 5. Typical good trace of velocity versus time from test performed in 70 feet of water in April 1975.

Table 2. Comparison of Field-Measured Penetrations to Penetrations Calculated From Data Taken in 70 Feet of Water

Test No.	Measured Penetration, P_m (inch)	Calculated Penetration, P_c (inch)	P_m/P_c
1	41.8	41.0	1.02
2	24.3	28.3	0.86
3	24.3	28.8	0.84
4	24.3	24.0	1.01

DISCUSSION

The purposes of the testing described in this report were (1) to demonstrate that the concept of using the Doppler principle to instrument a penetrometer was workable and that accurate data could be obtained and (2) to see if velocity and penetration performance were as expected.

The test data show that clear traces of velocity versus time, which are paramount in analyzing the data, can be obtained. Traces similar to those shown in Figure 4 would leave no hope of determining changes in deceleration, which are important in determining changes in strength. Conversely, traces similar to Figure 5 would give a good idea of deceleration changes. The interference in Figure 4 was caused by the receiving system and was not the fault of the sound source on the penetrometer. With all transmitting and receiving systems working properly, traces with quality equal to Figure 5 should always be obtained.

The tests reported give an indication of the accuracies that can be obtained with the Expendable Doppler Penetrometer. For the tests performed in 100 feet of water (see Table 1), the calculated penetrations are from poor velocity records similar to Figure 4, and the measured penetrations were from poorly defined mud lines on the penetrometer body. As a result the measured penetrations averaged 12% more than the calculated values. Better average agreement was obtained for the tests in 70 feet of water (see Table 2), where divers were used to mark the depth of penetration of the penetrometer. The measured values averaged about 7% less than the calculated values. A 7% error represents about a 2-foot error when penetration is 30 feet – the penetration expected in soft clays. This is satisfactory accuracy for determining penetrability.

It is not possible from the data to determine how accurately strengths can be estimated. The data in Figure 5 shows that changes in penetration resistance can be measured. These changes are indicative of strength changes. However, because the seafloor at the site where the data of Figure 5 was gathered is sand, no in-situ strength data are available.

When tests are performed at sites where soil strength data are available, checks of strength estimates from penetrometer data will be available.

The test that was attempted in 1,200 feet of water indicated that the terminal velocity of the penetrometer is about 80 feet per second. This is 20% lower than the design velocity of 100 feet per second. This velocity can probably be increased by smoothing the welds on the penetrometer body and by reducing the volume of the positively buoyant sound source system. However, a terminal velocity in the range of 80 feet per second should give 30 feet of penetration in soft clay which is about the required depth of the fluke of the CEL 20K explosive anchor to obtain its rated capacity in a soft clay. Such a result is satisfactory.

Because strength data are not available from the sites where the penetrometer has been successfully tested, penetration estimates calculated from penetration formulas could not be made. Therefore, penetration estimates that were made in the development of the penetrometer cannot be verified. However, because the data that were gathered on a mud flat in San Francisco Bay with model penetrometers compared well to the prediction method, this lack of verification is not of concern at this stage in developing the penetrometer.

While the testing that has been done demonstrates the workability of the instrumentation concept, there is a factor that affects the physical phenomenon of a Doppler shift of a sound frequency. The relationship of this factor – the sound velocity v_s – to the frequency shift is shown in Equation 1. The equation shows that the frequency shift for a given penetrometer velocity is a function of the velocity of sound in the medium in which the penetrometer is traveling as well as the velocity of the penetrometer. Therefore, sound velocity changes must be accounted for to prevent data errors.

The terminal velocity before impact must be calculated. For water, a change of 300 feet per second in the sound velocity (the greatest expected) will cause a 3.1% error in the frequency shift when a midrange value of 4,800 feet per second is assumed. Hence, there will be a 3.1% error in the calculated terminal velocity. However, for most cases, this error can be reduced to less than 1% by using sound-velocity-depth-latitude charts. If the terminal velocity of each penetrometer is found to be nearly the same, this error can be eliminated and the sound velocity of the water calculated from the terminal velocity and the frequency shift using Equation 1.

In soil, large changes in sound velocity are possible. Fortunately, in the soft clays and oozes that comprise most seafloors the sound velocity is within ±2% of that of the bottom water. Hence, the assumption that the sound velocity in these soils is the same as the bottom water will result in only small errors. These soft materials can be identified by deep penetrometer penetration. In sands and stiff clays the sound velocity can be 6 to 7% more than that of the bottom water. These soils can be identified by shallow penetration and the sound velocity adjusted accordingly. This adjustment applies only to penetrations greater than the length of the penetrometer because until the penetrometer is fully embedded the acoustic projector is in seawater, not soil. In general, it seems that reasonable estimates of the sound velocity can be made to minimize errors from this factor.

CONCLUSIONS

1. Using a Doppler instrumentation system to monitor the kinematics of a free-falling penetrometer is workable.

2. Accurate determinations of penetrometer penetration can be made using the Doppler instrumentation system.

3. The Doppler instrumentation system is capable of showing change in resistance to penetration which is indicative of soil strength changes.

4. The expendable Doppler penetrometer reaches a terminal velocity of about 80 feet per second which, based on penetration theory, is sufficient to attain about 30 feet of penetration in a typical deep ocean clay (red or pelagic clay).

5. Factors that affect the Doppler frequency shift will not cause large errors in the data and can be reduced to an error of a few percent with proper data interpretation.

FUTURE PLANS

Twenty Expendable Doppler Penetrometers will be fabricated on contract.* These units will be tested at a variety of locations and in a variety of seafloor soils. They will be tested in soft clay (1,200-foot site and perhaps 5,600-foot site), in firm clay (Seacon I site), and in a sandy-silt (Seacon II site) which are all near Port Hueneme. Testing will also be performed in both a deep ocean red clay and calcareous ooze. These deep ocean tests will be conducted in conjunction with other projects that plan to visit sites for gathering soil data or to test the CEL 20K deep water anchor. The test program outlined will provide comprehensive information on the performance of the Expendable Doppler Penetrometer. The results of the tests will be analyzed and reported.

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* Prototypes of these units have been delivered. Tests have shown that they meet all specifications.

ACKNOWLEDGMENTS

The Doppler instrumentation system which was the key to obtaining a rapidly deployable and expendable system was conceived and developed by John R. Thompson of the Instrumentation Center at the Civil Engineering Laboratory.

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