The MIT/Marine Industry Collegium
Opportunity Brief #27

Offshore Geotechnical Evaluation

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OFFSHORE GEOTECHNICAL EVALUATION

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PREFACE

This Opportunity Brief and the accompanying Workshop (held on December 10, 1981 in Houston, Texas) were presented as part of the MIT/Marine Industry Collegium Program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 90 corporations and government agencies who are members of the Collegium. The underlying studies at MIT were carried out primarily by the members of the Constructed Facilities Division of the Civil Engineering Department at MIT and are more fully reported in the references cited herein. The author is responsible for this abridgement.

Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant, at (617)253-4434.

Norman Doelling

July 15, 1982

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1. An Invitation to Cooperative Research

Over the last six years, research programs at MIT have made important advances in geotechnical analysis as it relates to the design of offshore structures. In general, this work deals with new ways of measuring the properties of offshore soils, predicting the ultimate capacity of offshore piles, and with quantifying the uncertainties that arise in connection with estimating the engineering properties of soils.

The results of these research programs point toward key developments in analysis and instrumentation that should lead to better and more economical ways of conducting geotechnical evaluations and deriving engineering data. The field studies are extensive for an academic program, and include some important "at-sea" experiments. However, further development is required, together with wider testing and application of these techniques in parallel with on-going exploration and geotechnical evaluations. Carried out as a cooperative effort among one or more geotechnical exploration companies and our team of investigators, this developmental work should result in early adoption of these techniques in the arsenal of technological tools for American companies.

Thus far, the research has been supported in large part by the Federal Government (the NOAA Sea Grant Office), by a U.S. corporation of Dutch origin (ERTEC, formerly FUGRO Consulting Engineers) and a Venezuelan government agency (INTEVEP).

Recently, some limited support was provided by three geotechnical consulting firms in the Boston area: Geotechnical Engineers, Inc.; Goldberg, Zoino and Associates; and Haley and Aldrich, Inc. Furthermore, most of the hardware used in this research is developed, manufactured and supplied to MIT by Geotechnique Int., Inc. In the interest of maintaining the United States' competitive status with other oil-producing nations, it would be mutually advantageous for university researchers and representatives of the U.S. offshore industry to work together in the further extension and validation of the work reported here.

This Brief and the associated Workshop held in Houston on December 10, 1981, provide an overview of the research programs. Each section, with the exception of 4, is an edited version of relevant Sea Grant Research Reports, intended to give the reader an overview of the efforts to date.

Section 2 presents a summary of an extensive field and laboratory testing program aimed at developing and calibrating new in situ testing devices. It also briefly outlines MIT efforts in the development of more reliable interpretation methods for predicting the engineering properties of soils from the data generated by the different in situ tests.

Section 3 describes a new instrument - the piezocone penetrometer - for in situ testing of soils. The device provides continuous, simultaneous measurements of the cone resistance, skin friction, and pore pressures during cone penetration. The piezocone penetrometer has been tested in two deposits and appears to offer a great potential as a soil exploration tool, especially offshore where time is expensive.

Section 4 addresses a recently established research program aimed at improving existing methods for predicting the ultimate capacity of offshore friction piles in marine sediments and hence provide more reliable design methods for offshore structures. This is achieved via a combination of experimental studies with a new piezo-lateral stress cell and developments of improved predictive methods based on more realistic models of clay behavior.

Finally, section 5 deals with quantifying the variability of soil-property estimates gathered by field measurement and integrating that information into a comprehensive, quantitative analysis of the geotechnical risk in offshore structures.

2.0 Exploration & Evaluation of Engineering Properties for Foundation Design of Offshore Structures

2.1 Introduction

In 1976, the Constructed Facilities Division at MIT initiated a research program aimed at improving geotechnical capabilities in the investigation of offshore sites. The focus was on evaluation of existing in situ tests and the development of more reliable methods and devices for determining the values of soil parameters necessary for foundation designs involving cohesive sediments. The development of new measuring devices required a new theoretical approach to the variables being measured and to the engineering properties of clays. Extensive field and laboratory tests were required to provide correlation data with the theoretical results.

2.2 The Research Program

The electrical (Dutch) cone penetrometer (8)* and the pore pressure probe (6,13) represent a new generation of in situ testing devices for offshore use. These devices combine the benefits of simplicity, consistency, and economy. However, their applications in medium to soft clays lacks a solid base of evaluated experience, especially in the U.S.A. This research program was designed to provide a well-defined basis for analysis. It consisted of three components:

1. Performance of Dutch cone and pore pressure probe tests on several representative soil types for which there already exists extensive information about in situ undrained stress-strain-strength behavior.
2. Development of improved theoretical methods for relating Dutch cone penetration resistance and pore pressure measurements to the engineering properties of clays.
3. Interpretation of the results of the measured cone penetration and pore pressure data with the improved theoretical models in light of the known undrained stress-strain-strength behavior of the soils, leading to preparation of guidelines for the use and interpretation of Dutch cone test data.

A summary of the results obtained to date are provided herein.

NOTE: * ( ) refers to References listed on page 27.

2.3 Onshore In Situ Measurements

Extensive penetration testing was conducted in three onshore sites having different and well established in situ undrained stress-strain-strength behavior. These measurements, performed using the electric cone penetrometer and pore pressure probe, were aimed at identifying the important parameters affecting cone penetration and providing a comprehensive data base that can be used along with analytical techniques to predict the engineering properties of soils required for foundation designs.

Results (6,7) show that measurements of the cone resistance, q_c and pore pressure, u, are repeatable and very valuable to: a) distinguish between different strata even in the difficult case of consecutive layers of slightly different clays having different stress histories and/or frequencies of sand lenses; b) detect the presence of thin soft and/or pervious layers which might strongly affect foundation designs; and c) provide a good description of soil variability (scatter) affecting design reliability.

As an illustration, consider the q_c and u data measured at a site consisting of peat, sand and heavily dessicated clay and presented in Fig. 1. Individually, q_c and u records detect major changes in soil strata, but jointly, they have an excellent potential for soil identification as well. For example, in the peat, q_c is low and u is high, whereas in the relatively clean sand, q_c is high and u is very close to the hydrostatic values, u_o.

This suggested the use of the ratio u/q_c as a parameter for detecting stratigraphy, soil identification and variability. Results also indicate that u/q_c correlates reasonably well with the stress history of clays (6). Moreover, pore pressure decay data after steady penetration stops offer additional information regarding the consolidation and/or permeability characteristics of soils.

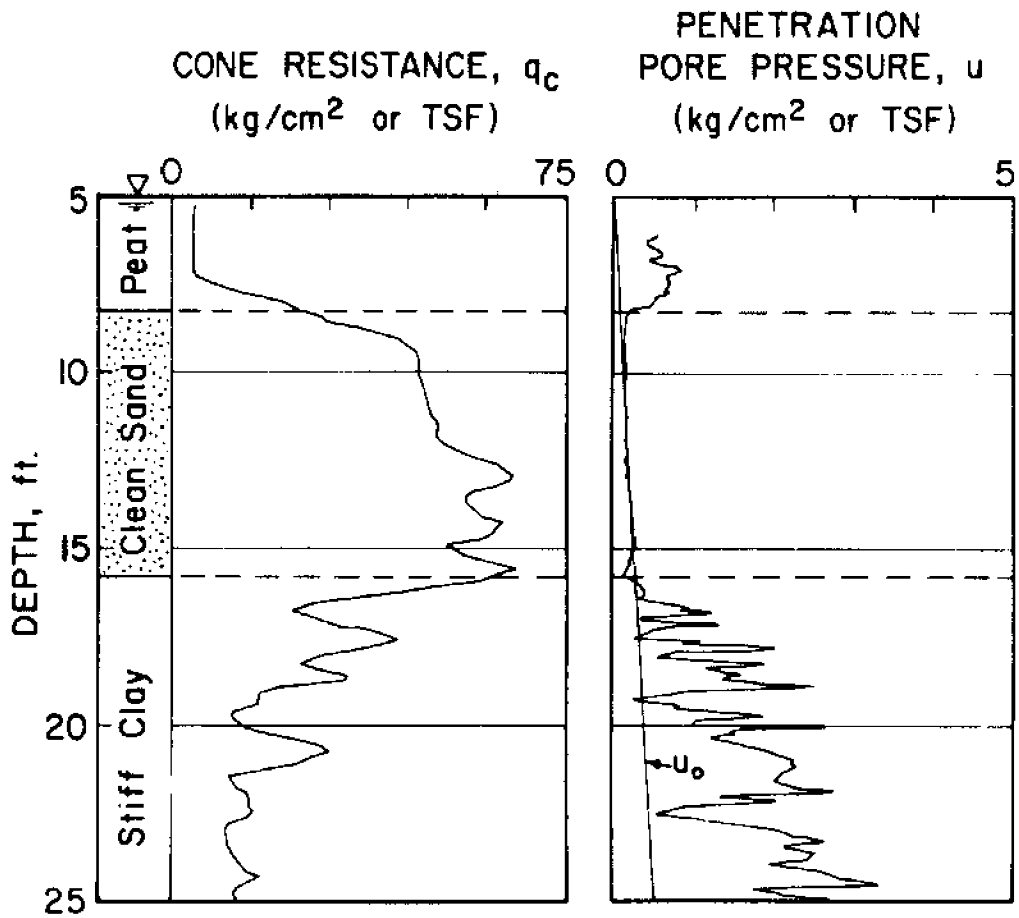

Figure 1. Cone Penetration in Soil Profiling

2.4 Offshore Penetration Tests

Having evaluated the electric cone penetrometer and pore pressure probe in three onshore sites with widely different properties, and having established that both devices provide repeatable and consistent data, it was then decided to assess their potential as offshore exploration tools. In the summer of 1979, an effort was undertaken to determine the foundation conditions and pertinent soil engineering properties at several "virgin" sites offshore Venezuela. The effort consisted of:

1) soil borings with high quality undisturbed sampling and in situ testing involving the electric cone penetrometer and the pore pressure probe. This represents the first time penetration pore pressures were measured offshore.
2) "sophisticated" laboratory testing program according to the SHANSEP procedure (an acronym for Stress History And Normalized Soil Engineering Properties; see Reference 9) in order to establish more reliable soil parameters.
3) analyses to attempt to correlate the results of the in situ tests with the soil properties established from the laboratory testing programs.

Results obtained at two widely separated (120 km) sites containing a thick deposit of soft, plastic "Orinoco Clay" that covers vast areas offshore Venezuela show that (1, 4, 10):

1) generally, similar mineralogical compositions are obtained at both locations, thus indicating reasonably similar source materials and depositional environments.

2) essentially identical, well defined profiles of maximum past pressures are measured throughout the deposit.

3) the SHANSEP procedure provides a much more reliable estimate of the in situ properties of the Orinoco Clay than obtained from conventional "strength index" tests (e.g. lab vane, Torvane, etc.) which exhibited extreme scatter.

4) the cone resistance and pore pressure profiles measured during cone penetration yield a more detailed picture of soil stratification than possible with undisturbed sampling and laboratory testing.

The nearly identical results obtained from both the in situ and SHANSEP test programs conducted at widely spaced borings as well as geological considerations strongly suggest that vast areas of the Orinoco Clay should have very similar engineering properties. This important conclusion should enable substantial cost savings since future site specific exploration programs within the deposit can mainly utilize relatively inexpensive in situ testing.

2.5 Interpretation of Cone Penetration Data

An extensive effort was devoted to theoretical developments required for the interpretation of the cone penetration data. A semi-empirical theory was developed (7) to predict the undrained shear strength of clays from measurements of cone resistance and pore pressures during cone penetration. The theory accounts for the tip angle, tip enlargement and clay anisotropy. An evaluation of theoretical predictions was made by comparing the predicted undrained shear strength s_u (cone) to s_u (reference) based on the SHANSEP procedure (9) and/or actual foundation failures. The theory predicts reasonable upper and lower bounds of the strength. However, predictions can be improved if pore pressure measurements are also included (7).

Furthermore, empirical correlations between q_c and the undrained shear strength obtained by the field vane test are developed for the sites tested in MIT's research program and six additional Scandinavian sites (7). These correlations depend on the soil type, stress-history and depth.

A new and economical method has been developed for estimating the coefficients of consolidation and permeability of cohesive soils from measurements of the pore pressure decay that takes place after cone penetration is interrupted (5). In this technique the initial excess pore pressures developed due to cone penetration are estimated by means of the strain path method (12) - an approach that consists of combining the strain path of soil elements with appropriate constitutive laws to determine the different field variables. Dissipation of these pore pressures is evaluated by means of the finite element method and theoretical dissipation curves are developed which are then matched with the measured decay curves to compute the consolidation and permeability characteristics of the soil.

The method was evaluated by means of extensive dissipation measurements in two clay deposits. The predicted profiles of the consolidation and permeability coefficients provide good agreement with laboratory data and full scale performance (5).

3.0 The Piezocone Penetrometer - A New Instrument for In Situ Testing

The potential of using cone resistance and pore pressures in soil exploration has led a number of institutions (e.g., the Building Research Station in England, the Norwegian Institute of Technology in Norway, Laval University in Canada) to develop a single cone that can measure these properties simultaneously. The piezocone is such a device. It measures the skin friction, f_s, in addition to q_c and u.

3.1 Penetrometer Description

The piezocone penetrometer illustrated in Fig. 2 has a 60^{o} apex angle with a 10cm^2 base area and contains a porous stainless steel tip connected hydraulically to a pressure transducer for measuring the pore water pressure. The force required to push the cone is measured by a load cell located behind a porous stone. The friction sleeve consists of a freely rotating hollow cylinder of area 225 cm^2 and is equipped with a load cell for measuring the friction force. Depth is recorded as an electrical signal. All data are displayed on strip chart recorders for observation during field operations and are also recorded on magnetic tapes for subsequent computer processing.

The penetrometer is equipped with a protection device to avoid overloading the load cell measuring the cone resistance. The features incorporated in this piezocone allow adoption of a sensitive cell (say 1 ton capacity) and, should a hard layer be encountered, protection pins shear, thereby protecting the cell. Such an event is readily detected from the output signal and a higher capacity load cell can be easily installed.

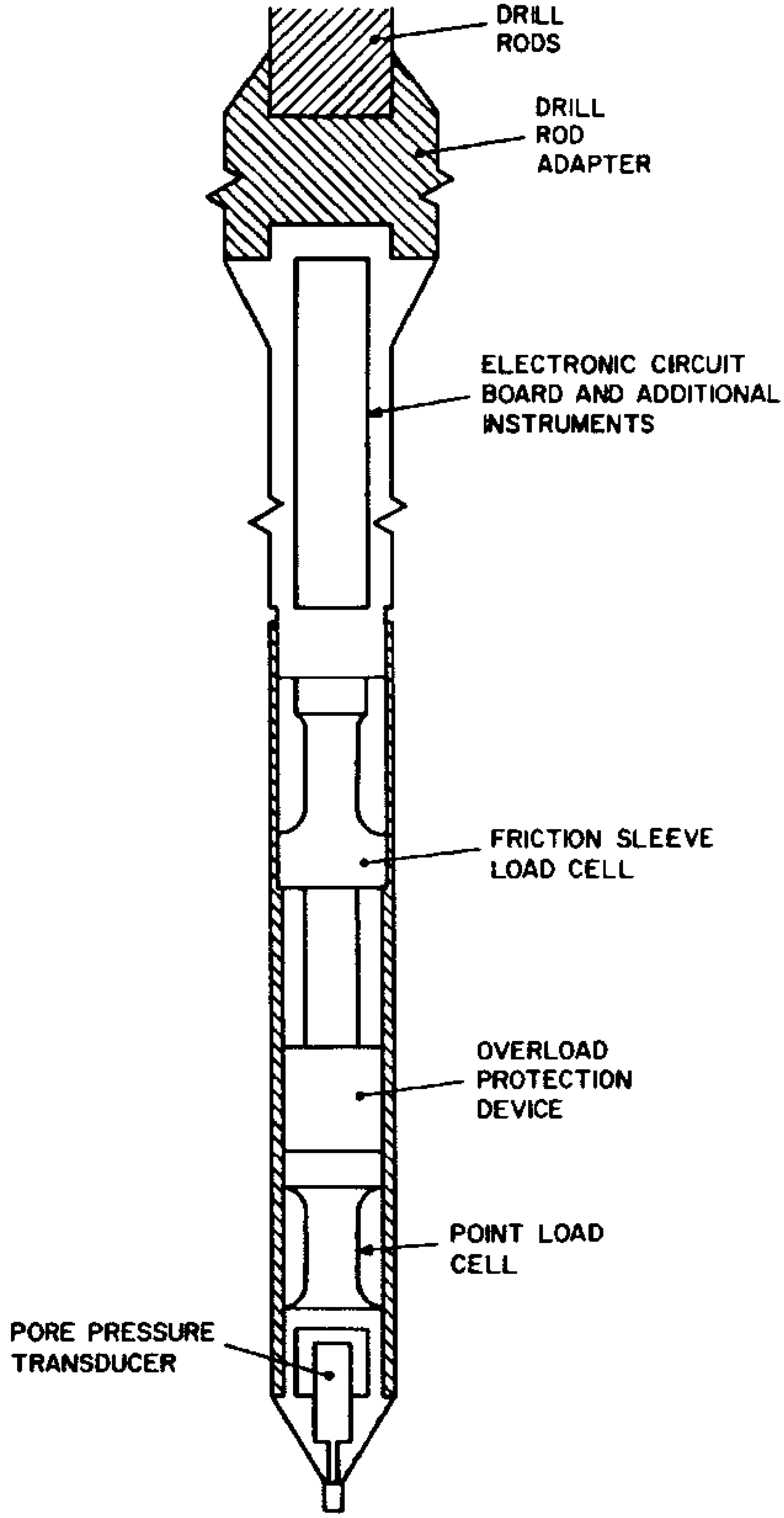

Figure 2. The Piezocone Penetrometer

3.2 Results to Date

The piezocone penetrometer was evaluated in a marine illitic clay deposit of established engineering properties. Extensive previous cone penetration measurements were also available. The following conclusions were reached (3):

1. The cone penetration records obtained by the piezocone are essentially similar to those previously determined separately by the electric cone and piezometer probe.
2. The porous stone located at the tip of the piezocone for measuring the penetration pore pressure has no effect on the cone resistance.
3. The cone penetration data are repeatable and consistent. Since a continuous record is provided, the piezocone allows a good definition of soil variablity and stratification.
4. The piezocone is particularly useful in detecting interstitial layers that can be important in the assessment of stability and drainage boundaries for foundation designs.
5. With u and q_c being measured simultaneously in the same hole, the ratio u/q_c reflects changes in soil stratification. Furthermore, and as mentioned previously, the ratio may reflect changes in the overconsolidation ratio within a clay deposit.
6. The reliability of skin friction measurements in clay deposits seems to be questionable.

3.3 In Situ Testing Facility on the MIT Campus

MIT has recently established a facility on the campus for carrying out geotechnical in situ testing. The facility will allow MIT and other institutions to calibrate and evaluate testing devices as developed and will provide a valuable teaching and training ground for students.

Tests including the piezocone penetrometer and the field vane were performed at the facility during the fall of 1981. In addition, in situ measurements of the total horizontal stress and pore pressures were made using the Piezo-Lateral Stress cell (described in Section 4) and undisturbed samples were recovered for subsequent laboratory testing. Results are currently being analyzed and evaluated.

4.0 Ultimate Capacity of Offshore Friction Piles in Clays

4.1 Introduction

Piles represent the most common foundation type used in difficult soil conditions (e.g. soft clays) and hostile environment (e.g. offshore). The prediction of the ultimate axial capacity of a single pile is the first step in deep foundation design wherein soil resistance is provided at the tip (point resistance) and along the shaft (skin friction). For long piles in clays, the point resistance usually constitute a small fraction of the pile capacity and, for most practical purposes, is adequately predicted by existing methods. The major portion of pile capacity is thus derived from skin friction along the shaft, especially when no competent end bearing layer exists. Therefore, the limiting skin friction that can be provided by the soil is the primary factor governing the design of piles in deep clay deposits.

However, the prediction of skin friction on piles is extremely difficult because of the complicated nature of the soil-pile interaction. Designs are presently performed on the basis of conservative engineering intuition developed from general experience and the results of load tests conducted mostly on single piles onshore. As a result, a large uncertainty and scatter exist in the predictions of the currently available design methods.

In 1980, a research project was initiated at MIT to attempt to improve existing procedures for predicting the ultimate capacity of axially loaded fricton piles in clays and hence provide more reliable design methods for offshore structures. This is achieved via a combination of experimental studies on model piles and development of improved predictive methods based on more realistic models of clay behavior.

4.2 In Situ Measurements on Model Piles

A new device, the Piezo-Lateral Stress cell (PLS cell), has recently been developed at M.I.T. Figure 3 shows the PLS cell which consists of two basic units:

1) a cylindrical lateral stress cell to measure the horizontal total stress, σ_h, on the shaft of a model pile. The cell consists of an outer steel membrane that transmits the soil pressure to a thin chamber filled with water where the pressure is measured via a pressure transducer, and;
2) a high air entry stainless steel porous disc to measure the pore pressure, u, at the interface between the cylindrical shaft and the soil.

The main advantages of this PLS are:

1) it is very rigid and has exactly the same geometry as a circular pile shaft;

2) measurements of σ_h and u are obtained simultaneously, and hence provide the detailed variation in effective horizontal stress, $_h$, during penetration, after penetration stops when consolidation takes place, and during subsequent shearing (e.g. additional penetration or shaft rotation), and;

3) the response time of both $\bar{\sigma}_h$ and u is very rapid.

Hence, the cell provides a means of measuring directly the horizontal effective stress and its variation with time, which represents the major uncertainty in existing prediction methods and is considered invaluable to this research.

The PLS cell has been recently used in a slightly over consolidated deep deposit of Boston Blue Clay. Continuous simultaneous measurements of σ_h and u were taken during cell penetration, consolidation and subsequent loading. Throughout the testing program, the cell assembly was located a distance of about 27 times the shaft diameter behind the tip, thereby eliminating any end effects. Preliminary results obtained during one of the consolidation phases of the testing program indicate that existing analytical solutions grossly overestimate the final effective horizontal stress acting on the pile shaft after consolidation is completed. Similarly, measurements taken during subsequent loading after consolidation is completed show that both pore pressure and total horizontal stress change during this process which contradict with assumptions inherent in some analytical methods.

Additional testing programs will be perfomed at other sites in order to obtain data covering the most important "soil characteristics" affecting the problem at hand. The results are expected to enhance our knowledge of the basic mechanisms controlling the pile-soil interaction and thus result in improvements of great practical and economic significance to existing pile design procedures, especially regarding very long piles where little empirical data exists.

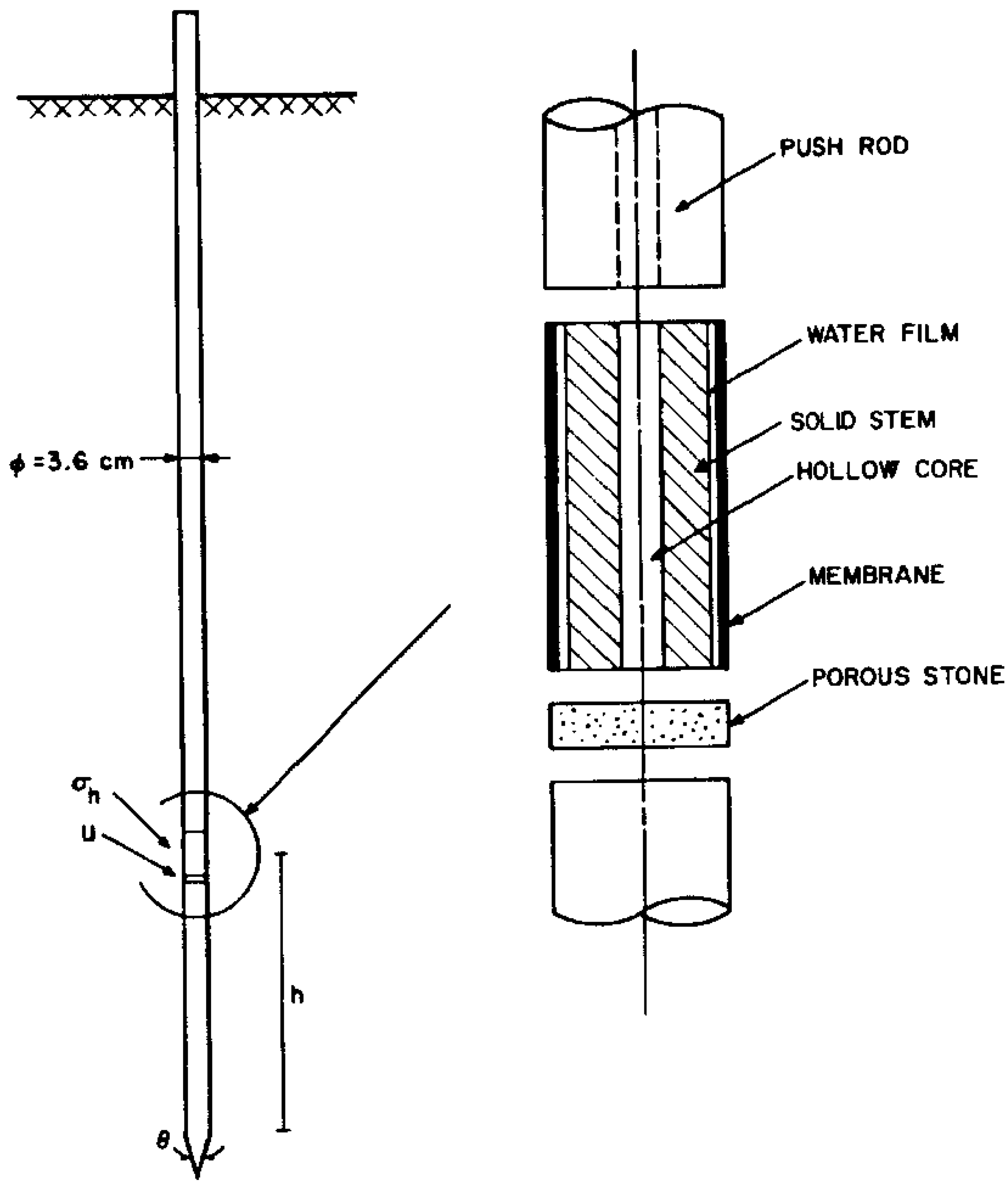

Figure 3. Schematic of the Piezo-Lateral Stress Cell

5.0 Quantifying Risk in Geotechnical Engineering

5.1 Introduction

The present work is an approach to the use of reliability techniques in the design process for offshore facilities (2). It includes a generic analysis of the uncertainties in such designs. The predictions of risk and reliability that result are, of course, partial. They do not include such things as negligence and gross error, nor do they include modes of performance about which basic mechanistic understanding is lacking. However, for the purposes of exploration, design and regulation they provide quantified analyses that allow partial optimizations and rational bases for decisions.

As with any engineering project, offshore facilities inevitably involve risks and are designed in the face of uncertainties. The recent surge in offshore development, particularly the move to deeper waters and more hostile environments, has led to a situation with even larger uncertainties than those of onshore counterparts. These uncertainties arise from environmental loadings (e.g., storm wave and earthquake), from inadequately understood physical mechanisms (e.g., structural and soil response), and from insufficient data to precisely characterize offshore sites (e.g., bottom parameters or storm recurrence rates).

These uncertainties are normally dealt with by designing for adequately high factors of safety against chosen design loads. This is done to assure that the available resistance of a structure is substantially greater than the loads it normally experiences, and also higher than the extraordinary loads which may occur in the life of the structure. However, because the loads actually to be experienced by the structure as well as the structural and foundation response to those loads are known only imperfectly, no matter how high the design factor of safety some probability remains that realized loads will exceed realized resistance, leading to partial damage or total collapse of the facility. The consequent costs of such failures can exceed the immediate structural damage, through oil spillage, other environmental impact, loss of service of the facility, and in certain cases human injury or death.

The questions, then, are what is the magnitude of this probability of damage or collapse, what are the significant sources of uncertainty, and what is the marginal cost of reducing risk? The work reported here deals specifically with geotechnical sources of risk. That is, with the principle sources of uncertainty affecting predictions of foundation performance, and with the aggregate uncerainty they lead to. To limit the breadth of coverage, the work has focused on gravity-type platforms, founded on the ocean bottom, held in place by their weight. While many offshore platforms are not of this type, being founded rather on driven piles, much of the present work applies to them as well.

The problem of risk offshore is complicated by the design philosophy of many owners and constructors of offshore platforms. Given the commercial nature of these ventures and limited design lives, there is understandably little incentive for the highly conservative design practice common in other large civil projects, for example, dams or bridges. Offshore facilities tend to be designed with an attempt to rationally balance financial risk of failure against marginal design modifications.

5.2 Outline of the Report

The main part of the report is organized in five broad chapters (2). The first presents an overview of the sources of geotechnical uncertainty in offshore structures, previous quantitative analysis of those uncertainties, and the philosophy of formal methods in geotechnical reliability analysis. The second and third examine the basic uncertain variables, dealing with environmental loads and their effects, and with site characterization and parameter estimates, respectively. Chapter 5 is an extended discussion of the problem of modeling foundation performance, and the uncertainties of that undertaking. Finally, Chapter 6 considers the aggregation of these uncertainties into overall estimates of risk and reliability.

To illustrate the analyses and methods developed in the course of the work, a specific site on the southern flank of

Georges Bank has been chosen for discussion. This site had been studied earlier, and was chosen for its location offshore New England, the availability of data, and its inclusion in potentially developable tracts. Specific information on the site has been introduced as needed throughout the report.

At the Workshop, Professor Baecher discussed an application of some of the statistical methods to the specific problem of using data from field measurement of foundation soil properties.

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