The MIT Marine Industry Collegium
Opportunity Brief #44

Capacity of Offshore Friction Piles in Clay

A Project of
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1.0 INTRODUCTION AND BUSINESS PERSPECTIVE

Tension leg platforms represent the transition in offshore structures from depending on compression members to relying on tension members, rather like the transition in bridges many decades ago from trusses to cable suspension design. Using piles in tension instead of compression creates new challenges, such as very large continuous loading and cyclic loading over many cycles. Solutions to these forthcoming problems require new procedures based on understanding soil and pile interaction, with the alternative being to take huge risks in building structures which cost hundreds of millions of dollars, or to spend additional millions in overdesigning for safety. However, there are major uncertainties in predicting pile behavior under normal conditions, let alone being able to extrapolate to untried situations in deeper water or different types of soil.

Over the past decade a major geotechnical study at MIT has probed the interaction between the friction piles used to support offshore structures and their underlying soils. This "MIT approach" combines analytical methods with measurements obtained by the new Piezo-Lateral Stress (PLS) cell to develop an effective procedure for analyzing and predicting the behavior of friction piles. Large-scale load tests at a site in Empire, Louisiana have verified this method, and proved the value of the PLS cell for measuring soil-pile interactions.

Professors Mohsen M. Baligh and Amr S. Azzouz of the MIT Department of Civil Engineering are elucidating the fundamental aspects of penetration to better understand the mechanisms governing the installation of piles, and to identify important factors controlling disturbance effects. This understanding is essential to develop more rational analysis and design methods for deep foundations. Initial efforts were devoted to compression piles, while their present project is concerned with tension leg piles. At the MIT Marine Industry Collegium Workshop in Houston, Texas, on January 22, 1986 they discussed their analytical work and field experiments.

2.0 ACCURACY OF EXISTING METHODS FOR PREDICTING PILE SHAFT BEHAVIOR AND CAPACITY

It is extremely difficult to rationally predict the limiting skin friction of piles because of the complicated mechanisms governing soil-pile interaction. Hence, current design methods are based on conservative engineering intuition developed by repeated trials and from the results of load tests generally conducted on relatively short piles on land. Existing empirical methods can easily differ by a factor of two in estimating the limiting skin friction, and are difficult to adapt to changing conditions such as longer piles or different soils.

In recent years the geotechnical profession has approached the problem of predicting limiting skin friction by investigating the changes in stresses and soil properties during different phases of a pile's life. Pile installation characterized by severe soil disturbances is followed by consolidation, when excess pore pressures arising from installation dissipate. Pile loading is the third stage.

Rational estimates of the limiting skin friction acting on the shaft of a pile in clay requires that the state of stress around the pile be quantified. The state of stress is a function of the initial conditions and the changes of stresses and pore pressures that occur during pile installation, subsequent consolidation, and loading. Predictions of these changes are difficult due to the complex mechanisms involved. Empirically derived factors have been used in the past to correlate limiting skin friction with known initial conditions.

These empirical factors have been backfigured from pile load tests which were generally conducted on land and reflect the particular test conditions such as method of installation, type of pile and length, nature of soil deposits, and the pile load test method. Such methods have proven satisfactory up to now. However, as oil production moves farther offshore, it is necessary to extrapolate these methods to a new environment complicated by higher loads, larger pile diameters and lengths, and different soil conditions.

Furthermore, issues of behavior under dynamic loading and the performance under tensile loading (as opposed to the more conventional type of compressive loading) need to be established. These changing conditions have led to a renewed interest in the development of a rational method for predicting the axial static capacity of such piles.

Empirical correlations of load test data represent the backbone of present design methods for friction piles in cohesive soils. Until sufficiently accurate procedures and/or simpler experimental techniques for estimating pile capacity are developed, load tests will retain their pivotal role in designs. Therefore, the reliability of design procedures and their continued development are intimately related to the quality and completeness of pile load test data. Without a comprehensive description of other important aspects of soil and pile shaft behavior, the interpretation of results and experiences achieved at a given site cannot be reliably extrapolated to other deposits or used to improve existing design methods.

Empirical methods relate the limiting skin friction to a measurable or quantifiable parameter, such as the undrained shear strength or vertical effective stress, by a factor derived from pile load tests. These methods can be broadly classified into total stress, effective stress, or mixed approaches. Presently the most widely used method for offshore work was established in the American Petroleum Institute's "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms" (1981). Representing more than 30 years of accumulated experience by the offshore oil industry, it specifies different factors according to plasticity indices of the clays involved. The empirical parameters backfigured from the results of pile load tests in principle incorporate the effect of all factors affecting the limiting skin friction: the type of clay, stress history, dimensions, method of installation, time effects, etc.

Faced with the challenge of computing axial pile capacities for offshore environments where there is little or no load test experience, researchers became interested in the development of systematic methods. An understanding and assessment of the stress and strain history of the soil through the various phases in the life of a pile is required to quantify the effective stresses existing during working conditions. Researchers are aware that these effective stresses and hence the shear resistance of piles in clay increases with time due to pore pressure dissipation and soil consolidation. However, the time needed to reach the maximum resistance varies significantly with pile type and soil properties, notably permeability and compressibility. Consolidation analyses estimate the changes in the effective stresses at the pile/soil interface during and after consolidation because these stresses are a controlling factor on the ultimate shaft resistance.

One of the main thrusts of Professors Baligh's and Azzouz's work is to improve the accuracy of existing methods for predicting pile shaft behavior and capacity. "The tendency among engineers is to choose a pile capacity from pile load test results or other geotechnical data which feels appropriate to them. After using the same procedure repeatedly, people tend to feel comfortable with a certain average more from familiarity than from understanding the process," says Professor Baligh.

In some sense this method works, since platforms do not routinely tumble down in the ocean. However, this good record could also very well be due to costly overdesigning, as Professor Baligh explains. "For a long time, the general rule for selecting offshore pile foundations is to take the biggest possible hammer and the biggest possible pile and drive it to the greatest penetration depth." In most cases that very conservative method works, although it can run up enormous unnecessary costs, and involves unknown margins of safety. Professor Baligh says, "The demand for our work comes from people who are undertaking projects that are either new, bigger, or subject to different conditions where the experiences of the past cannot be directly extrapolated."

By and large, design methods were empirical until 1975, says Professor Baligh. From 1975 to 1980 the oil industry spent considerable amounts of money trying to improve the understanding of the pile soil interaction. "Unfortunately, the research during those five years relied on an overly simplified approach that was not commensurate with the order of difficulty of the problem. People came up with different types of predictions that we thought were not sufficiently realistic to be valuable for practical purposes. They had different estimates of what happened during consolidation, without fully considering what happened during installation before the soil consolidated. The installation problem begins when the pile is pushed in. Since the installation is usually treated in a very simplified and crude way, the consolidation results also are not very reliable."

3.0 THE "MIT APPROACH" FOR PREDICTING PILE SHAFT CAPACITY

The initial step in deep foundation design is to predict the ultimate axial capacity of a single pile. For long piles in clays, a significant portion of pile capacity is derived from skin friction along the shaft, making the limiting skin friction provided by the soil of primary importance in pile design. Combining theoretical methods with measurements obtained from the Piezo-Lateral Stress (PLS) Cell, the "MIT Approach" develops an effective procedure for analyzing and predicting the behavior of friction piles.

3.1 The Piezo-Lateral Stress Cell

While analytical procedures provide valuable insight into important mechanisms affecting soil-pile interaction, there is currently a dearth of accurate and reliable measurements of the stresses acting on pile shafts, even though these measurements are necessary to carefully evaluate theoretical predictions.

The Piezo-Lateral Stress (PLS) cell provides simultaneous measurements of the average shear and normal stresses as well as the pore pressures acting on cylindrical pile shafts. "Predictions of pore pressures involve significant uncertainties. Measurement with the PLS represents a valuable addition to the reliability of our overall procedure," says Professor Baligh. "The device measures what we want with sufficient accuracy for us to believe and incorporate into predictions."

The PLS makes it possible to evaluate the horizontal effective stress, which is the parameter considered to dominate pile behavior, and the shear stress betweeen the pile and the soil. Not only can it provide essential fundamental data on piles behavior in clays, but it is also an exploration tool for directly estimating the shaft resistance of cylindrical piles at a given site. Laboratory evaluation of the device reveals an instantaneous time response that is believed essential for obtaining reliable results.

A fundamental aspect in the design of the PLS cell is its reduced interference with the quantities being measured. For example, the finite amount of water exchanged between the soil and a pore pressure measuring device constitutes interference. Such interference can be reduced if the flexibility, or amount of required water exchange, is reduced to a minimum. Similarly, in measuring the total horizontal stress, it is important that the deformation of the measuring system be negligible. This requires a very stiff measuring system which must also be sensitive to imposed stresses. Rigidity is ensured by having a solid steel core and only a thin internal water film to which the externally applied pressure is transmitted.

In situ measurements with the PLS cell in slightly overconsolidated Boston Blue Clay indicated that pile installation significantly reduced the effective horizontal stress acting on the shaft. The total horizontal stress on the shaft decreased significantly during consolidation, contradicting predictions of linear consolidation theories. In Boston Blue Clay, values of the effective horizontal stress after soil consolidation were close to the estimated initial conditions existing prior to installation. The effective horizontal stress on the pile shaft decreased significantly during pile loading to failure.

Right now Professor Baligh and colleagues are planning a project with MIT Sea Grant using the PLS behind an open-ended pile. All the previous PLS measurements were taken on a closed-ended tip that did not allow the soil to enter the core. Offshore piles are cylindrical steel open-ended piles up to two meters in diameter. The open end pushes in the soil rather like a giant cookie cutter, forcing part of the soil inside the tube and squeezing the rest outside.

Professor Baligh considers it important to study both closed-ended and open-ended modes. "We expect to see a big difference compared to earlier PLS data on closed-ended tips, especially in the time required to reach dissipation of pore pressures. Open-ended penetration influences a small zone around the pile, whereas close-ended penetration deforms the soil in a large zone. The consolidation of excess pore pressure and the gain in strength of open-ended penetration is much faster."

In its current form, the PLS is a very sensitive and delicate piece of equipment. It breaks easily in sand or gravel, although with proper care it can be taken to any site in clay soil. (Professor Baligh adds that a new cell can be built specifically for sand tests.) Used for practical design purposes, the PLS gives essential information about the behavior of the piles to be tested at a given site. The PLS as a research tool indicates esssential features of pile shaft behavior. At tests in Empire, Louisiana, the PLS results indicated that the assumed capacity of the test piles was less than the true capacity, because excess pore pressure had not fully dissipated as expected and the effective stresses had not yet reached their final value.

3.2 Strain Path Method

Installing deep foundations and in situ test devices in the ground disturbs the soil. Many factors complicate the development of reliable methods to predict these disturbance effects, including large deformations and strains in the soil observed in laboratory and in situ conditions; very complicated behavior of soils including nonlinearities, inelasticity and anisotropy; the presence of pore water requiring the treatment of the soil as a multiphase medium; and difficulties associated with of the soil-indenter interface characteristics.

Thanks to better identification and understanding of the important mechanisms governing foundation behavior, there have been significant improvements over the last 30 years in predicting the behavior of shallow foundations. Essential elements for enhancing predictive capabilities include newly developed analytical procedures, advances in the understanding and formulation of soil behavior, better methods to characterize in situ soil conditions, and more reliable observations of field prototype behavior.

The Strain Path method is an approximate analytical technique to predict soil disturbances caused by installing test objects in the ground. The method provides a comprehensive framework that enables these problems to be approached in a realistic, systematic, and rational manner, according to Professor Baligh.

Observations of soil deformations caused by the undrained penetration of rigid objects in saturated clays led Professor Baligh to hypothesize that, due to the severe kinematic constraints in "deep" penetration problems, soil deformations and strains are generally independent of the shearing resistance of the soil. These problems are essentially strain-controlled and imply that even when relatively simple soil properties are used to estimate deformations and strains caused by penetration, the errors introduced are expected to be reasonably small. Approximate stresses and pore pressures can then be computed by assuming realistic soil behavioral response and by satisfying equilibrium conditions. Exact stresses and pore pressures would be obtained if and only if the estimated soil deformations were identical to those experienced in the actual problem. The latter generally depend on soil behavior (unless the problem is fully strain controlled) and cannot be exactly known a priori.

The essential features and strong similarities of the Stress and Strain Path Methods in approaching geotechnical problems are described in Table 1. The Stress Path Method is an approximate analytic technique commonly used to predict the stability and deformation of "shallow" foundations such as footings, mats, excavations, natural slopes, earth dams and other situations where the depth of the soil below ground surface is relatively small compared to its lateral extent. This method provides an integrated, systematic and simple framework for elucidating and solving shallow foundation problems, and its widespread use in geotechnical practice as well as teaching offers ample evidence of its real merit.

TABLE 1

COMPARISON OF STRESS PATH AND STRAIN PATH METHODS

<table>
<tr><th>Stress Path Method</th><th>Strain Path Method</th></tr>
<tr><td colspan="2">Applications</td></tr>
<tr><td>Shallow problems: Depth of soil of interest is relatively small compared to its lateral extent.</td><td>Deep problems: soil of interest is relatively deep below ground surface compared to its lateral extent.</td></tr>
<tr><td colspan="2">Steps</td></tr>
<tr><td>1. Estimate initial stresses.
2. Estimate incremental *stresses*.
3. Perform stress path tests on samples (or use adequate soil model) to obtain strains at selected locations.
4. Estimate deformations by integrating strains.</td><td>1. Estimate initial strains.
2. Estimate incremental *strains*.
3. Perform strain path tests on samples (or use adequate soil model) to obtain effective stresses at selected locations.
4. Estimate pore pressures by integrating equilibrium equations.</td></tr>
<tr><td colspan="2">Approximations</td></tr>
<tr><td>In Step 2 stresses are approximate leading to path-dependent deformations in step 4, i.e., strains violate some compatibility requirements.</td><td>In Step 2 strains are approximate leading to either 1) path dependent pore pressures in Step 4, i.e., total streses violate some equilibrium requirements; or 2) effective stresses that violate some constitutive relations.</td></tr>
<tr><td colspan="2">Iteration (improvement of solution)</td></tr>
<tr><td>Use results of Step 3 to improve estimates in Step 2.</td><td>Use results in Step 3 to improve estimates in Step 2.</td></tr>
</table>

Taken from M.M. Baligh, "Strain Path Method," *Journal of Geotechnical Engineering* 111:9, Sept. 1985.

Basic steps of the Stress Path Method are outlined in the table to estimate deformations in shallow foundation problems, emphasizing the consequences of simplifications. A key element in the method's popularity is that shallow problems are essentially stress-controlled. Thus, estimates of stress increments based on simple soil properties such as linear elasticity generally involve small errors that can be tolerated by the engineer predicting foundation performance.

Information for applying the Strain Path Method to "deep" problems is also provided in Table 1. The method is virtually identical to the Stress Path Method except for one fundamental aspect that really represents the difference between shallow and deep problems: the stress controlled nature of shallow problems as opposed to the strain controlled nature of deep problems. The basic simplification introduced by the Strain Path Method consists of hypothesizing that estimates of strain (instead of stress) increments based on simple soil properties will introduce errors that are small in comparison to other major questions in soil behavior.

Using the MIT approach (PLS and strain path method) is not simple and requires computer programs and sophisticated analyses. However, Professor Baligh says, "Our methods are slowly seeping into practice. A number of organizations have asked for our help to predict the pile capacity in important and critical site conditions using our analytical and experimental capabilities."

4.0 THE EMPIRE EXPERIENCE: APPLICATION OF MIT TECHNIQUES IN THE FIELD

Even though Empire, Louisiana, is on land, its soil deposits are considered typical of the clays in the Gulf of Mexico where hundreds of offshore oil platforms already stand or will be built. Starting in the 1970s, a consortium of oil companies have carried out a systematic set of pile load tests at Empire, including a large scale pile load testing program to evaluate design methods.

"We were attracted to Empire because the comprehensive set of load tests offered us the opportunity to evaluate our procedures and techniques for predicting the capacity of piles in clays," says Professor Baligh. "Since the pile load tests had already been done, we proposed to predict the capacity of those piles based on our work at MIT. Our predictions were made before we looked at the results of the pile load tests. Then we attempted to evaluate our prediction methods by comparison with the pile test results."

What resulted from that work in 1983 "actually was the inverse of what we expected," says Professor Baligh, even though the Empire data represented one of the the best documented histories of pile load tests in this country. Instead of evaluating the prediction methods using the pile load test results, he ended up having to reevaluate the conditions and results of the pile load tests on the basis of their predictions.

Unless the test conditions are fully controlled, nobody can evaluate the prediction method, Professor Baligh explains. Also, without fully understanding the problem to start with, it is impossible to plan a program involving pile load testing that totally controls all the important conditions. If at the end of the work the researcher finds that one or two important factors were not measured and/or evaluated during the process, the evaluation and usefulness of the test results are severely undermined.

Using the results of a laboratory analysis on soils retrieved from Empire, Professor Baligh and colleagues predicted the behavior of the model pile (PLS cell) in Empire clay. They then returned to the Empire site to evaluate their predictions under conditions similar to the original Empire pile load tests.

The water pressures that develop during the pile installation dissipate gradually, and it had been assumed during the test that these pore pressures would have completely dissipated. "Our results indicate that these pore pressures did not dissipate for the pile load tests, and therefore the piles tested had not developed their full capacity to bear weight. In the records of experiences regarding pile capacity, we found that the important values of the capacity of those piles tested at Empire were smaller than they should have been," Professor Baligh mentions.

Because of such errors, the literature underestimated the actual capacity of the piles after full dissipation of the excess pore pressures. "We increased the estimated capacity of the piles as they were reported in the literature.

That revision was an important milestone in the area of pile foundations, especially large diameter offshore piles. Now we have a better picture of how these piles perform, and we can provide the geotechnical profession with more reliable interpretations of these very expensive tests."

To predict capacity in a given offshore site, a test pile is driven on shore, loads are measured, and the results are extrapolated according to the conditions prevailing at the offshore site. Accurate extrapolations require knowledge of the soil conditions at both the test and intended sites.

"We found that the available data bank based on pile load tests and presently used to design offshore piles involves so many uncertainties in interpreting the pile capacity, and so much scatter in the test data, that it is not accurate. To improve the state of the art would require conducting more careful pile load testing programs, in which one controls all the conditions and measures all the important factors. Then when data is extrapolated to a new condition, the engineers can change the parameters in the prediction method to suit the site and conditions," states Professor Baligh.

"In this research we have identified the important parameters that we need to measure and/or control," continues Professor Baligh. For the pile shaft capacity he specified seven parameters and two functions of time that must be measured or controlled to give sufficiently reliable test results. These important characteristics of the pile and soil influence their interactions, and should be measured in a pile load test. Professor Baligh says, "We feel that the horizontal effective stress, i.e. the grain-to-pile material contact stress after all the excess pore pressures have dissipated in the soil, is the most important parameter on the pile shaft. If all excess pore pressure dissipates, the horizontal effective stress will control the frictional resistance of the shaft."

Piles have been used for thousands of years. "However, we understand now what makes the piles work, and how to test and better design piles in the future," Professor Baligh believes. The costs of pile foundations are horrendous and piles are a major foundation type, especially for offshore construction. By understanding pile behavior, engineers would be able to design for actual conditions rather than having to plan enormously costly overdesigns for nonexistant contingencies. "Our most important contributions are developing a better understanding of friction pile behavior, and providing the geotechnical profession with the theoretical means and practical tools to advance its knowledge."

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