Small-scale models of friction piles in a soft marine clay

Modéle à petite échelle de pieux de frottement dans une argile marine molle

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ABSTRACT: Instrumented small-scale models of piles were developed at the National University of Mexico with the intention of investigating the fundamental behavior of friction piles in clay. In particular, they are oriented to study the piled foundations for offshore platforms of the jacket type in the Sound of Campeche (Gulf of Mexico). The goal is to better our understanding on load transfer mechanisms, effect of cyclic loading, permanent displacements and ageing effects, among other aspects. Also, the intention is to verify experimentally, under lab controlled conditions, analytical solutions.

RÉSUMÉ: Des modèles à petite échelle de pieux instrumentés ont été développés à l'Université Nationale du Mexique, dans le cadre d'une rècherche sur le comportement fondamental de pieux de frottement dans des argiles. Les essais sont orientés à l'étude des fondations sur pieux des plateformes off-shore du type jacket dans la sonde de Campêche (Golfe du Mexique). L'objectif est d'améliorer, entre autres, les connaissances sur les mécanismes de transfert de charge, l'effet du chargement cyclique, les déplacements permanents et le vieillissement. Les essais permettront par ailleurs de vérifier la validité des solutions analytiques dans les conditions contrôlées du laboratoire.

1 INTRODUCTION

Foundations for offshore platforms of the jacket type in the Sound of Campeche (Gulf of Mexico) are usually solved by tubular piles, 42 to 72 inches in diameter, with reaching depths down to 125 m below the sea floor. Given the stratigraphic conditions of the zone, most of the bearing capacity of the piles is provided by shaft friction. Common design approaches are those developed for other stratigraphic and marine environments around the world. It has been considered convenient to review the pertinence of such procedures, from the geotechnical point of view. The strategic role and high cost of these essential exploration and production oil structures oblige to reduce the uncertainties in the geotechnical analysis and design.

The instrumentation of prototype piles in an actual offshore foundation is being considered; however, it was deemed important to carry out first an investigation using pile models. This experimental program (now in progress) was developed to obtain a better understanding of the behavior of friction piles, making use of instrumented small-scale models of almost 1-m long, and 2.7 cm in diameter. The instrumentation was aimed at measuring state variables such as axial forces and bending moments along the pile, as well as total radial stress and pore water pressure at the soil/pile interface, at three different depths. The measurement of these variables allow us: (i) to make the comparison of measured normal stress on the pile shaft and those given by theoretical predictions; (ii) evolution of total and neutral pressures at the soil/pile interface; and, (iii) pile/soil transfer mechanism of load, including the mechanism of degradation of skin friction due to prolonged cyclic loading. The testing program covers a wide range of static and dynamic loading conditions. Axial and lateral cyclic loading are intended to consider the actions of storms, wind, hurricanes and earthquakes.

The design of the experiment is presented in this paper, including the artificial preparation procedure of a marine clay bed in a 97 cm-diameter chamber, in which the piles will be driven and tested. The pneumatic closed-loop digital servo control loading system and the data acquisition system are also described. The clayey soils were sampled from the sea bottom, and then mixed with seawater, reaching at the beginning a slurry consistency. Subsequent processes of sedimentation and K_o-consolidation produced an intact soft clay artificial sediment

2 ANTECEDENTS WITH MODELS OF FRICTION PILES

A large number of lab testing programs have been carried out with scale models, in order to investigate the static and cyclic behavior of piled foundations. So, Mayne et al. (1995) performed cyclic lateral loading tests under controlled loading, as well as static tests with controlled displacement. McManus et al. (1994) tested models, inducing cyclic axial loading with frequencies between 0.01 and 0.2 Hz, and loading amplitudes ranging 10 to 90% of the model pile maximum capacity. In both cases, the models were of small scale, 2 to 3 cm in diameter and less than one m long. They included total stress transducers or load cells, depending the parameter to be measured. However, Procter and Khaffaf (1987) have recognized that it is necessary to install more than two sensors for measuring a specific variable. Obviously, although this is desirable, the economic aspect should be also considered. Maybe it is best to choose and combine two different sensor types among the measurement points.

3 GENERAL APPROACH OF THE EXPERIMENT

Our tests are oriented to measure the internal or state variables of the phenomenon in models or scaled portions of friction piles in the laboratory. These measurements will help us to set the example for theoretical and numerical modeling for the foundations response. The models consist of a profusely instrumented aluminum tube, 2.64 cm in diameter, and 90 cm long. Initially, we will study a single pile, but then, they will be part of a group with up to four pile models. In a gravitational environment, it is not possible to fulfil the relationships between prototype and model, according with the similitude laws; that is why centrifuges are used. Recognizing this, to reproduce the effect of vertical stress acting in the soil around actual piles, an external axial pressure will be applied to the surface of a reconstituted soil, which is contained in a large chamber. In this way, the piles can be subjected to a range of stresses representative of the actual field pressures.

Piles in marine environments are usually designed with the API standards. Axial capacity of piles in clayey soils is related to a value of strength lower than the undrained shear strength. For the case of lateral loading, the proposed analytical expressions involve an dimensionless empirical coefficient in terms of the pile depth, for both static and cyclic loading. This approach in terms of total stresses has clear limitations, that emphasizes the need to improve our knowledge, in order to explain and design friction piles, in terms of effective stresses.

Following this approach, the described instrumentation includes not only total axial load cells and total normal pressure cells on the shaft, but miniature pore pressure transducers located in the shaft wall-soil interface. Jardine & Chow (1996) have proposed analytical expressions for determining the bearing capacity of piles for offshore platforms, in terms of effective stresses. They have proved their validity by means of field tests and tests with an instrumented pile model (Bond, Jardine & Dalton 1991). That contribution is a basis for the planning and interpretation of the experimental program described herein.

4 GENERAL DESCRIPTION OF THE EXPERIMENT

The characteristics of the experiment are in agreement with the goals of the project. The general layout of the experiment is shown in Figure 1. The following five components are recognized: the O-97-500 chamber, the reconstituted marine clay, the instrumented pile model, the automatic data acquisition system and, the electroneumatic system with digital servo control for applying axial and lateral loads.

The artificial soil was contained in a cylindrical steel chamber, whose denomination recognizes its 97 cm in inner diameter, and the 500 kPa, which is the design maximum axial pressure. The material in its initial condition was a clay-sea water mixture with a water content two and a half times its liquid limit. A mud consistency was reached, and so drained to an assembly formed by the chamber and two additional cylindrical extensions. In that time, this mixture reached 2.48-m height. Through sedimentation and then consolidation processes (Mendoza et al. 2000), the soil has being gaining consistency, and reducing remarkably its height. The soil is now in the chamber under the last consolidation stage, acting an hydraulic jack on the top surface. As a sub product of this research, theoretical and numerical development was done, thinking in related engineering problems, like those on hydraulic dredging, mud handling, and industrial, mining or municipal wastes (Mendoza et al., 1998).

Sweeney & Clough (1990) and Anderson et al. (1991) have emphasized the drawbacks of the *in-situ* studies, wherein the soil uniformity and stress conditions have uncertainties. This can be amended with chambers of enough size, for lab tests like those described herein.

Monotonic axial loading up to reach the failure, as well as cyclic loading are included in the scheduled tests. The following testing variables are foreseen: magnitude of the sustained load before the cyclic actions, amplitude of the dynamic loading, number of cycles, and frequency. The internal variables that will be measured under controlled conditions are as follows: axial internal load along the pile, total normal pressure and pore water pressure in the shaft-soil interface. Also, dynamic lateral tests are foreseen, with cyclic horizontal actions close to the head of the pile model. For this case, the models have flexural cells, recording so their bending characteristics. For both types of tests, stresses or strains can be controlled.

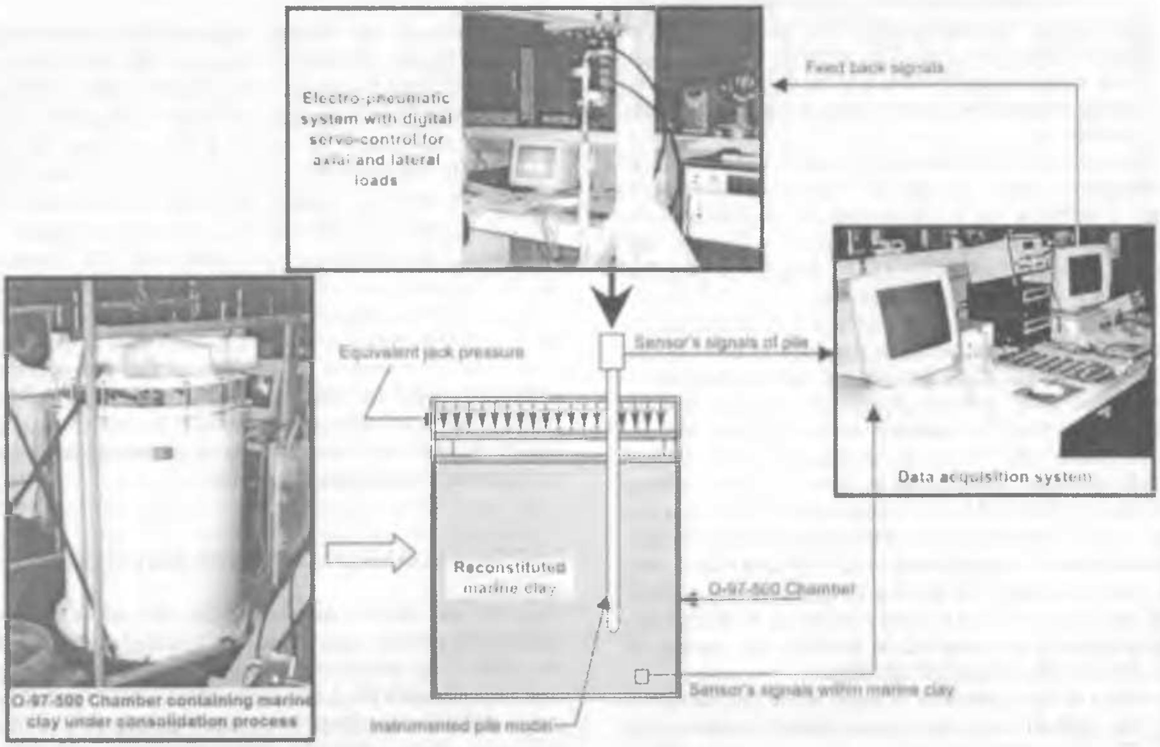

Figure 1. General layout of the experiment

The central idea for this experimental program is to measure the internal variables of the problem under controlled conditions, with the purpose of calibrating available analytical procedures or propose alternatives. As has been established, we do not attend to scale precisely the behavior of a prototype pile. We are aware that the similitude laws between the prototype and the model are not fulfiled, which is quite difficult in a common gravitational ambient. Centrifuges induce to the model accelerations various tens larger than the earth gravitational acceleration. In that way, stress states are imposed to the model, which are scaled to those of the prototype. In order to reproduce the stress level on the surrounding soil to piles, a hydraulic jack will be used reacting against a rigid cap to the chamber. It is considered that this condition is equivalent to test a portion of model to some particular depth; changing the level of applied stress, another depth would be represented.

5 DESIGN OF THE INSTRUMENTATION FOR THE PILE MODEL

5.1 *Pile model*

An aluminum tube, 2.64 cm in outside diameter, 0.28 cm in wall thickness, and 90 cm long, is the pile model. It is a continuous piece, Figure 2, having seven reduced sections as shown, wherein the strain gages (SG) are adhered. The selection of the strain gages was made considering the mechanical properties of the spring element, and the variable to be measured (Measurements Group 1988) In four of them, an axial load cell (LC) will be created; in the resting three positions, a flexural cell (FC) will be shaped. Additionally, four miniature pore pressure transducers (U), and four total pressure cells (TP) were included precisely on the shaft face. All the electrical wires of each SG are conducted thru the interior, for which a small hole was made next to the sensors. After the SG's were glued, and carefully protected, the reduced sections were cover with an epoxy-aluminum powder mixture. So, a constant diameter instrumented tube was obtained, and even with a similar superficial texture. The instrumented pile model is now being calibrated.

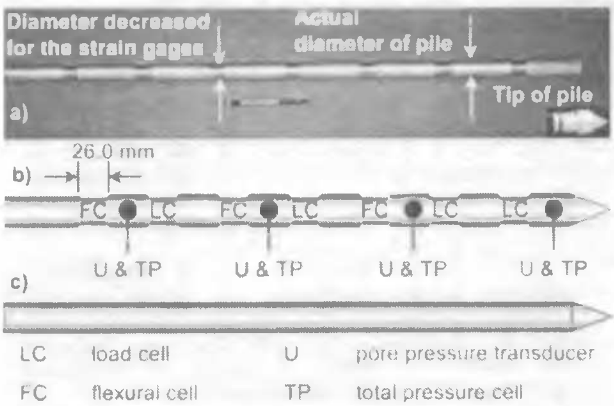

Figure 2. Distribution of the geotechnical sensors along the pile model

5.2 *Axial load cells (LC)*

Each axial load cell is constituted by four Mod. N24-13-5064L-350 strain gages, which are glued to the surface of the outside reduced section, 90° apart from each other and at the same level. Each SG measures both the longitudinal and transversal deformation of the tube wall. The arrangement of the gages is in full bridge, having in each branch two compensating sensors for compression and tension. Indeed, a cylinder under compressive action suffers a negative longitudinal deformation, and a positive diametral deformation.

Measuring the axial load to different depths, and assuming that the sliding surface is determined by the tube outside diameter, then the shear stresses along the shaft can be obtained. This shear stress can be related to the normal effective stress on the shaft, which is just the difference between the total stress and the pore water pressure.

5.3 *Flexural cells (FC)*

Flexural cells were installed in a similar manner than the load cells, although with a three SG array, to the same level and 120° apart from each other, forming each SG a quarter of bridge. The flexural cells will define the deformed shape of the pile model under lateral loading. Thus, it will be possible to measure the tube deformation in three directions, and also to compute its deformation vector. In each position, unidirectional Mod. CEA-13-250UN-350 strain gages were installed.

5.4 *Total pressure cell (TP)*

Total pressure cells based on SG can be of two types: for displacement, or with diaphragm. The pressures that will be measured in the model are relatively low; therefore, a sensor of the later type was considered convenient (Dally et al., 1984). In this case the diaphragm is very small and circular, monolithically built with its body, also in aluminum. Under uniform pressure, a tangential positive deformation $\varepsilon_{\theta\theta}$ occurs in the entire diameter, with a maximum value at the center. A negative radial deformation ε_{rr} is developed in the perimeter (embedding), as it is shown in Figure 3. Considering this deformation field, the Mod. N2A-13-5067F-350 circular rosette strain gage was selected. This gage is divided in four sectors, two in the center that measure the tangential deformation, and two in the perimeter oriented to measure the maximum radial deformation. Having four elements, a full bridge array is attained, as depicted in Figure 3.

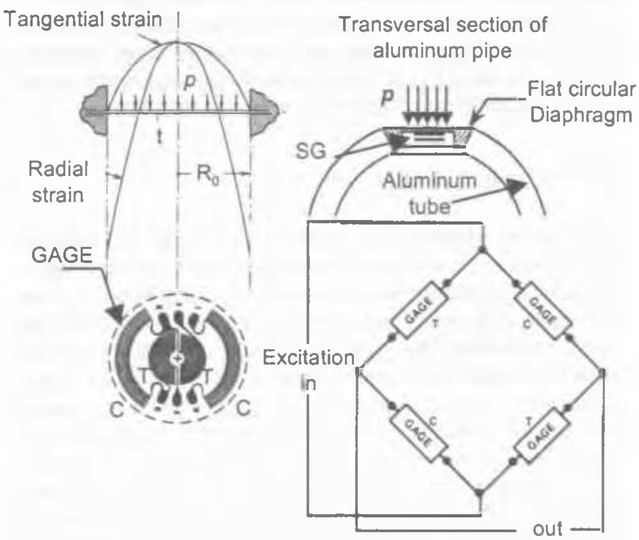

Figure 3. Total pressure cell of the diaphragm type, and its full bridge array

The rosette was glued in the inner and dry side of the diaphragm. The body of the TP was machined individually, under extreme care because the very thin diaphragm. Once instrumented this very small sensor, the body was glued to the wall of the pile model.

5.5 *Pore water pressure transducer (U)*

The pore water pressure transducers were placed in a similar way than the TP. A retention body was designed and built, according with the shape of the commercial miniature sensor, Figure 4. The body was also adhered to the wall of the pile model, with an epoxy resin. Between the transducer diaphragm and the surface of the model, a sinterized stainless steel porous element was placed; so, the flow of water is assured to the sensing diaphragm, avoiding the entrance of soil.

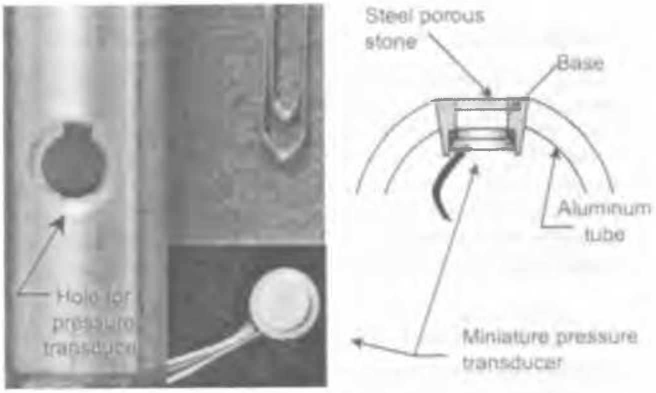

Figure 4. Pore water transducer in its retention body.

6 MANUFACTURE

The pile model testing demands small dimensions in their components, imposing difficulties in their machining tasks. Accordingly, a minute work was made, in order to assure correct response of the sensors. This was checked during the calibration of the model, for which known external actions were applied, and the corresponding signals were recorded.

A fundamental task for the correct behavior of strain gages is the sticking process. A rigorous sequence was followed: surface cleaning, aligning of the gage, temperature control, resin placement, and covering resins for sensor protection.

Wiring of the sensors demanded also particular attention because their large amount, and the reduced inner diameter. The LC, U and TP, each one has four fine conducting wires. The FC requires nine conducting wires for each one.

7 LOADING SYSTEM

The loading system is constituted by up to three pneumatic double acting pistons, two electro-pneumatic valves, a signal conditioning module, an analog/digital/analog board for the computer, a computer interface, and a servo amplifier for the valves operation. The system is completed by external load cells and linear displacement transducers of the DCDC type. This system is able to work under stress or strain controlled, and has the capacity to reproduce seismic or wave train records. The system can apply pulses with variable frequencies and amplitudes, as well as ramp, steps and sinusoidal functions. The servo valve is controlled by the system, sending the pneumatic pulses to the double room of the corresponding pneumatic actuator. The computer displays the output and input signals, and let us define the full conditions of the test.

When the test is being carried under stress controlled conditions, the master transducer will be the external load cell, located between the head of the pile model and the pneumatic actuator. If the test is being performed under strain controlled conditions, then the controlling sensors will be the corresponding DCDC, also placed in the pile model – piston connection. The pneumatic actuators are firmly fasten to a reaction frame

8 DATA ACQUISITION SYSTEM

The sensors in each pile model require 21 monitoring channels. Each cell demands a channel, except the flexural cells that need three each of them. Obviously, given the amount of channels and the dynamic nature of the tests, it was necessary to turn to an automatic data acquisition system. It is constituted by multiplexors, plug-in boards, chassis, power suppliers, and a personal computer. The system feeds to each channel in an individual basis, with the particular voltage, according with the manufacturer suggestions, and the conditions imposed during calibration.

The complete system is able to capture the signal up to 128 channels, with a maximum rate of 20,000 samples per second. It has enough capacity for conducting the static and dynamic tests. During the process, in real time, the computer displays the main parameters of the test.

9 CONCLUSIONS

The pile model testing offers a convenient alternative for knowing, under imposed stress or strain controlled conditions, the internal or state variables that define the behavior of friction piles. A comparison with theoretical results, for the same imposed conditions, gives elements for validating available procedures and developing new alternatives.

In this study, measurement of effective stresses on the model shaft is emphasized. Additionally, defining the axial loads to different levels along the pile model, it will be propitious to learn about the load transfer mechanisms from the pile shaft to the surrounding clayey soil.

The idea is to explore this experimental source through an ample testing program with a pile model, and a four-pile group, driven in a reconstituted marine clayey soil. The study is oriented in particular to piled foundations for offshore platforms, located in the Sound of Campeche, Gulf of Mexico.

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