Behaviour of open-ended pipe piles in sand during installation and loading

Le comportement des pieux tubulaires à extrémité ouverte dans le sable pendant l'installation et le chargement

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SYNOPSIS: An experimental study was performed to investigate the physical processes which influence the axial load capacities of open-ended steel pipe piles in sand. A double-walled pipe pile was developed to allow independent determination of the stresses on its inner and outer surfaces. An electronically operated single acting air hammer was developed for pile driving. Measurements were made of pore water pressures adjacent to the inner and outer walls, as well as side shear on the inside and outside.

INTRODUCTION

One of the major difficulties in predicting the axial load capacity of pipe piles in sand is the lack of understanding of the physical processes which control the behavior of piles during installation and loading. Variations between measured and predicted pile capacities arise due to a number of factors such as: severe changes in soil properties and state of stress caused by pile driving; difficulties in measuring field soil properties, particularly in the marine environment; variations in loading details and pile installation procedures; uncertainties in the behavior of the soil core (plug) during driving and subsequent loading; and soil structure interaction (Iskander and Olson, 1992, and Lehane and Jardine, 1994).

Designers account for these factors by calibrating simple theoretical models using empirical factors. The accuracy of this approach has been evaluated by comparing the predicted pile capacities to the measured pile capacities of known case histories. The scatter between measured and predicted pile capacities is significantly larger for piles in sand than piles in clay (Dennis and Olson, 1983a and 1983b). The primary inadequacy of this empirical approach is the data base used to calibrate the design method (Pelletier *et al.*, 1993 and Olson, 1990). At the present time, the data base has fewer load tests than the number of degrees of freedom of the pile-soil system, which precludes determining a unique set of calibration factors (Olson and Iskander, 1994).

Analytical studies, alone, cannot resolve the uncertainties in axial capacity predictions due to the complex nature of pile behavior. An experimental study of the physical processes which control the behavior of piles during installation and loading was performed in order to resolve some of the issues involved (Iskander, 1995). A brief description of the developed apparatus and test results is presented in this paper.

EXPERIMENTAL SETUP

Piles were installed and load tested in a pressure chamber which was filled with fine, Oklahoma sand using dry pluviation. The sand had uniformity and curvature coefficients of 1.5 and 1.15, respectively; and was placed at a density of 17.6 kN/m3, which corresponds to a 94% relative density. The chamber is 0.90 m in diameter and 1.05 m high. Horizontal and vertical pressures, up to 275 kPa, can be applied to the sand. The sand can be saturated with de-aired water which is supplied at the base of the chamber.

A load-controlled MTS feedback control system was used to apply static and cyclic loads via a hydraulic actuator. The system has a compressive capacity of 260 kN, and a tensile capacity of 200 kN. The pressure chamber is located on a loading frame, centered below the hydraulic actuator. The frame has a dynamic design capacity of 270 kN.

This investigation utilized a number of experimental techniques which are different from previous studies, and are discussed next.

Double-Walled Pipe Pile

Attempts to measure the load transfer along the length of open-ended single-walled pipe piles are complicated by the inability to differentiate the shearing stresses acting inside and outside the pile. A double-walled steel pipe pile was developed to allow independent measurements of stresses acting on its inner and outer surfaces, as well as pore water pressures at the internal and external at the interfaces (Fig. 1). The pile is 0.87 m long, 89 mm in outside diameter, and has an 8 mm wall thickness. The pile is instrumented with 40 strain gages and eight pore-pressure transducers, which were designed to survive pile driving

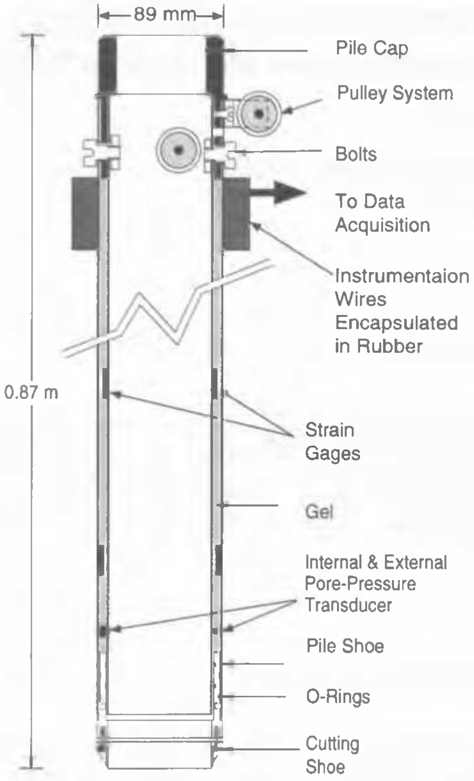

Figure 1. The instrumented double-walled pipe pile

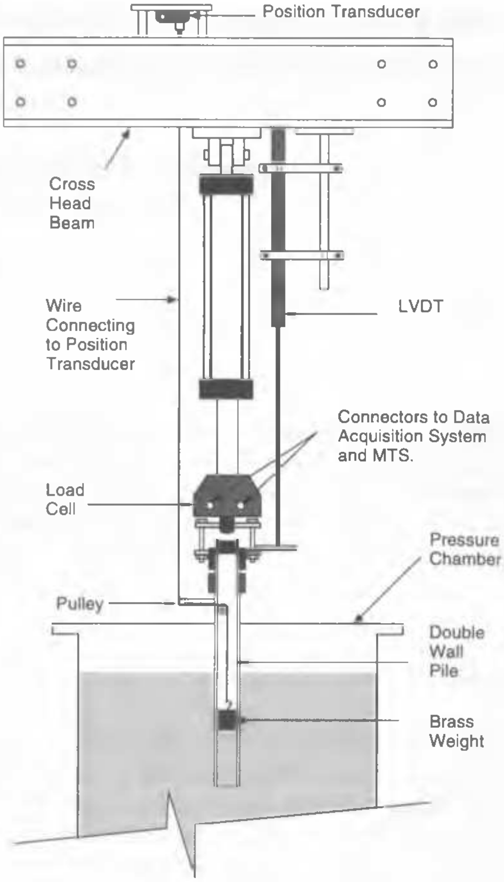

Figure 2. Instrumentation for load, displacement and plug movement

Electro-Pneumatic Pile Hammer

During installation, the dynamic interaction between the pile and surrounding soil may greatly influence the state of stress and soil conditions near the installed pile (Nunez *et al.,* 1988). Both dynamic and diffusive mechanisms occur when piles are driven. Dynamic effects deal with the inertial forces developed in the soil to resist pile penetration. Diffusive effects deal with the buildup and dissipation of pore water pressures during driving.

A fast electro-pneumatic hammer capable of representing the phenomena which occur during pile driving was built (Iskander, 1995). The hammer delivers a rated energy of 212 Joules with 57% efficiency. The hammer can operate with the full design energy at frequencies up to 1.2 Hz.

Elevation of The Soil Core Inside the Pile

The elevation of the soil core inside the pile was measured using a position transducer (Fig. 2). The transducer consists of a cable wound around a spring loaded shaft which is connected to a rotary optical encoder. When the cable is pulled out of the transducer, the shaft rotates and the magnitude of the rotation is registered by the optical encoder. The transducer has a simulated wheatstone bridge which converts the cable displacement into a voltage change.

Data Acquisition System

A MASSCOMP 5400 UNIX work station capable of sampling at 1 MHz was used for data acquisition. Analog Devices signal conditioning modules were used to amplify, filter, and isolate the sensors. A total of 31 channels were recorded as follows: axial and circumferential strains at 5 elevations on the internal and external walls of the pile (20 channels); pore pressures at four elevations on the internal and external walls of the pile (8 channels); and axial load, pile displacement, and elevation of the soil core inside the pile (1 channel each).

TYPICAL EXPERIMENTAL RESULTS

Approximately 30 load tests were performed using both instrumented and uninstrumented pipe piles. Due to space limitation, only a typical load test on a driven pile in saturated sand is shown here.

Driving Stage

Approximately 90 blows were required for installation. The pile did not plug at any stage of the driving process.

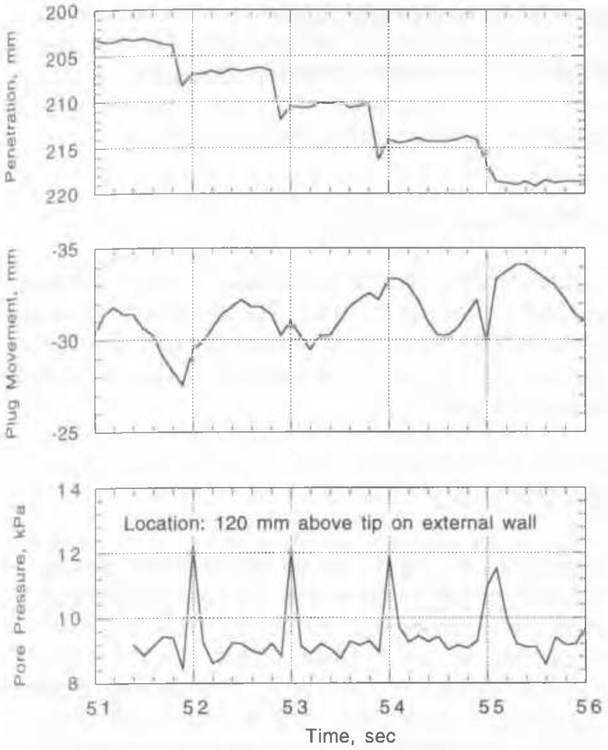

Figure 3. Penetration, plug movement, and pore pressure in four consecutive hammer blows

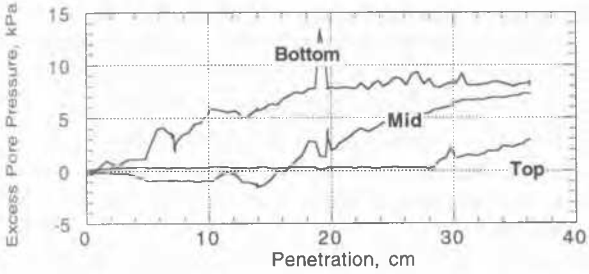

Figure 4. Build-up of pore pressures outside the pile during driving

The response of the pile-soil system during four consecutive blows in the middle of driving is shown in Fig. 3. The set per blow was approximately 4 mm. The frequency response of the position transducer used to monitor plug movements was slower than desired. However, it is clear that the plug continued to rise inside the pile after each blow. At the time of hammer impact, the measured pore water pressures rose by about 3 kPa in about 100 ms, and mostly dissipated in the next 100 ms. However, a gradual elevation in the pore water pressures existed between blows (Fig. 4). These residual pore water pressures rose to values of about 9 kPa (6% of the initial overburden pressure) at a height of 120 mm above the tip, on the outside, and up to about 10 kPa on the inner wall of the pile. Residual pore water pressures dissipated in about 20 minutes after driving ceased.

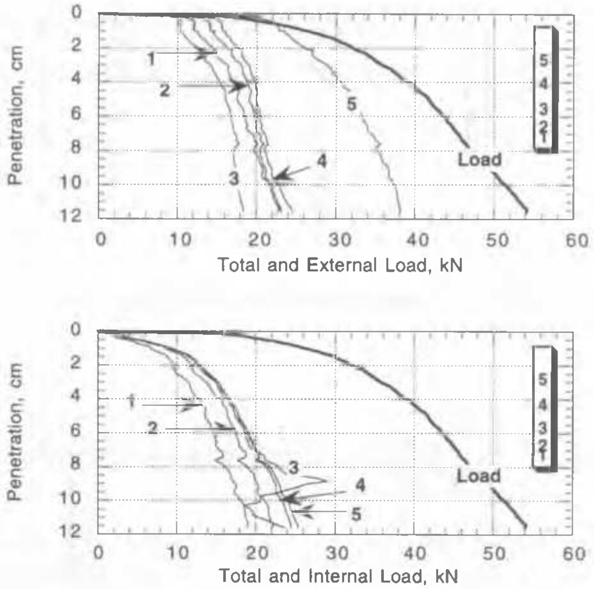

Figure 5. Load-settlement curve showing axial load transfer (a) outside and (b) inside the pile, during load test stage. Labels on contour lines represent elevations.

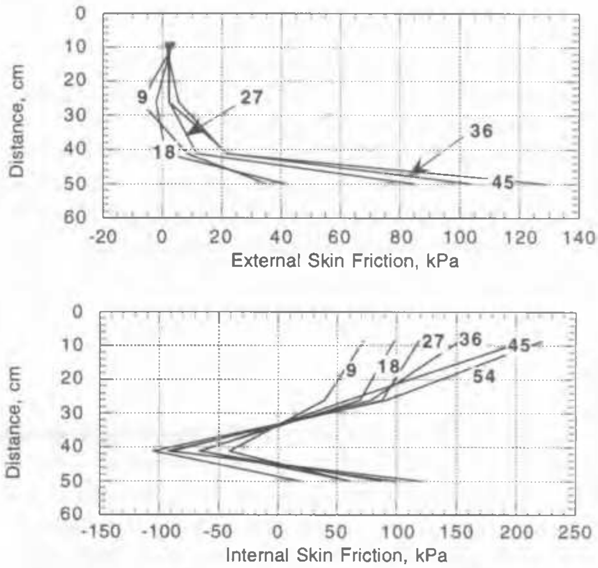

Figure 6. Skin friction distribution (a) outside, and (b) inside the pile during load test stage. Labels on contour lines represent applied load in kN

Load Test

The pile plugged during load testing and the surface of the soil core (plug) moved downward at approximately the same rate of penetration. Axial load transfer was continuously recorded during the load test (Fig. 5). The skin friction distributions shown in Fig. 6 were computed using the measured axial load transfer. Little skin friction developed in the top half outside the pile. Most of the load was transferred in end bearing which was transferred to the inner pile wall, by arching, in a

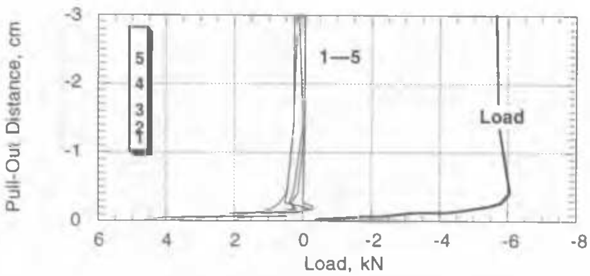

Figure 7. Pull-out curve showing axial load transfer inside the pile

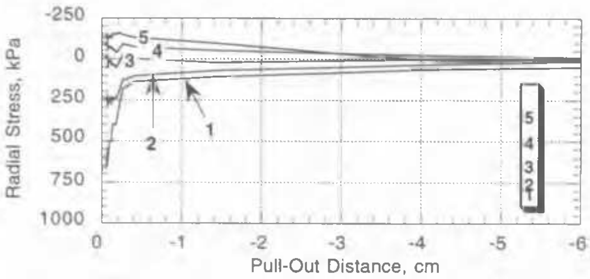

Figure 8. Radial stresses acting inside the pile during pull-out test

length equal to two pile diameters. Arching was accompanied by the development of large radial stresses (1000-1400 kPa) inside the pile (Iskander, 1995). A small build up of excess pore pressures occurred during the load test. Outside the pile, a maximum excess pore pressure of 5 kPa was recorded 120 mm above the tip. Excess pore pressures decreased with distance away from the tip.

Pull-Out Test

The pile's pull out capacity represented 20% of the capacity in compression and was developed entirely from friction outside the pile. The soil core (plug) was retained inside the pile during pull out, and essentially no plug slippage occurred. The plug contained large residual stresses which were released within 2 mm of the start of pull-out (Fig. 7). This observation was also supported by the measured radial pressure distribution inside the pile (Fig. 8). The pore pressures measured during pull out remained relatively unchanged.

CONCLUSIONS

The results of the testing program validate the performance of the developed apparatus, and provide unique insights into soil-structure interaction during pile driving and subsequent loading. Piles plugged during load tests, but not during driving. Plugging results in the formation of large radial stresses inside the pile. During pull out, only small pile movements were required to release the plug stresses. Pile driving resulted in a pore-pressure surge near the tip. The pressure surge resulted in a small build up of ambient pore pressure during driving. Excess pore pressures dissipated within 20 minutes from installation. A small build up of pore-pressure was also measured during load tests.

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