INTERACTION BETWEEN JACKED PILES IN CALCAREOUS SEDIMENTS

INTERACTION ENTRE PIEUX VERINES DANS LES DEPOTS CALCAIRES

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SYNOPSIS: Model tests on pairs of piles jacked into reconstituted calcareous sand have been performed to study the interaction behaviour of these piles during jacking, static and cyclic loading. The tests have been performed on medium-dense and dense samples of calcareous sand which have been consolidated under two different overburden pressures. Results of the tests are presented for the following aspects of behaviour: a) influence of a newly-installed pile on the force and displacement within an already-installed instrumented pile and b) the displacements and loads caused in the instrumented pile by static and cyclic loading of an adjacent pile.

The tests reveal that the interaction between the piles is dependent on the initial density of the soil and the spacing between the piles. During jacking, the residual loads developed in the adjacent pile increase as the sand density increases, while the direction of movement can change from downward to upward, depending on the soil density.

INTRODUCTION

Numerous static and cyclic laboratory and field tests on piles in calcareous sediments have been undertaken in the last two decades under various boundary test conditions (e.g. Angemeer et al, 1973; Nauroy and Le Tirant, 1983; Poulos, 1988a; Randolph, 1988; Al-Douri, 1992) to attain a better understanding of the behaviour of offshore piles in calcareous sand. However, the tests to date have concentrated on single isolated piles and with scant consideration given to the behaviour of pile groups and the significance of pile-soil-pile interaction.

This paper presents the results of laboratory model pile tests carried out to study interaction behaviour of piles jacked into medium-dense and dense reconstituted calcareous sand. Results are presented for the following aspects of behaviour: influence of a newly-installed pile on the force and displacement within an already-installed pile; the displacement and forces caused in a pile by static loading of an adjacent pile; the displacements and forces caused in a pile by cyclic loading of an adjacent pile.

SEDIMENT CHARACTERISTICS

The calcareous sediment used in these tests is referred to as N.R.A sand and was obtained from the North-West Shelf of Australia at the site of the North Rankin A platform. This soil had maximum and minimum particle sizes of about 2 mm and 0.06 mm respectively, and a mean particle size (D_{50}) of 0.15 mm. The minimum and maximum dry densities were 9.4 and 13 kN/m^3 respectively. The grading curve and the engineering properties of this soil obtained from static and cyclic shear box tests are presented by Al-Douri and Poulos (1992) and the properties from triaxial tests are given by Hull et al (1988). Microscopic examinations conducted by Allman (1988) have shown that the sediment is composed of a diverse range of particles, predominantly of bioclastic origin, with a high incidence of both intra-particle voids and thin-walled particles.

APPARATUS AND PROCEDURE

A diagram of the apparatus for the model pile tests is shown in Figure 1. The vessel containing the soil and piles had a 590 mm internal diameter and was 480 mm deep. The vessel was composed of three parts; a central vessel body containing the sediment sample, and top and base sections which were separated from the soil by a rubber membrane, and contained water which provided the confining pressure. The soil was consolidated initially by an equal applied pressure at the top and base boundaries. The inside wall of the vessel was lined with a stainless steel sheet to reduce the friction between the wall and the sand.

Two model piles of equal size, one instrumented and one uninstrumented, were made of 25mm external diameter aluminium tube, with a wall thickness of 3mm. A 45° solid aluminium cone was fixed to the tip of each pile. The instrumented pile consisted of 5 sections, and in each section, a group of four electrical strain gauges (forming a full Wheatstone Bridge circuit) was installed to measure the axial load. In addition, one group of strain gauges was installed very close to the pile tip measured the load carried by the tip. Loading applied via a loading machine and the head load was measured by a calibrated proving ring. The strain gauges were used to measure the forces along the pile during jacking of the instrumented pile and then during jacking of the other piles. All measurements were recorded using a micro-computer-based data acquisition system.

The sand bed was prepared by raining the sand through a special raining device placed on the body of the vessel, thus producing a relatively uniform sand bed (Al-Douri, 1992). The range of dry density produced by this raining procedure was 9.6 kN/m^3 to 10.5 kN/m^3, depending on the height of the sand fall. This range of density represented "loose" and "medium-dense" sand. "Dense" samples were produced by vibrating the rained sand in the vessel using two vibrators installed against each other on the top flange of the test vessel, as shown in Fig. 1. A dry density in excess of 10.5 kN/m^3 was obtained, with the actual value depending on the time of vibration. After placement of the sand, the desired overburden pressure was then applied for a period of at least 24 hours prior to pile installation and testing. Each test in this study consisted of following stages:

1) Jacking of the instrumented pile to a given depth (about 290 mm).
2) Jacking of the second pile to the same depth, and measurement of

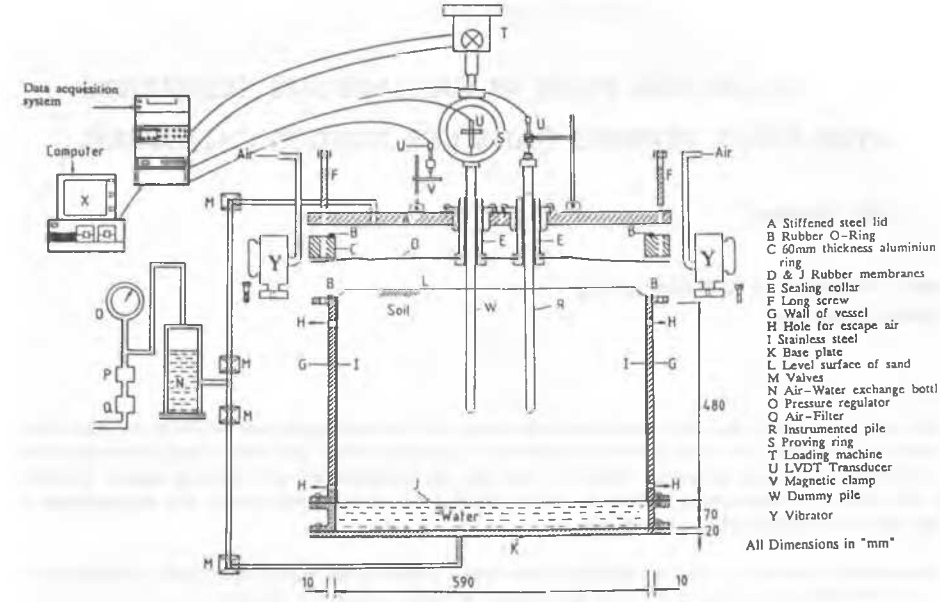

Figure 1 Schematic Diagram of Test Setup

the forces induced in the other pile.

3) Initial static loading of the 2nd pile to a displacement of 10% of pile diameter, which was assumed to be the failure criterion.
4) Cyclic loading of the 2nd pile, over a specific cyclic displacement, for between 50 and 100 cycles.
5) Final static loading of the 2nd pile to failure.

The rate of displacement was set constant for all the tests at 0.4mm per minute to avoid the effect of high loading rate on the pile capacity.

EXPERIMENTAL RESULTS

A total of 12 tests were carried out on model piles in calcareous sediment deposits of different densities, under two different overburden pressures. The first 4 tests involved jacking of four piles to observe the deflection of the first pile during jacking of the three other piles, while the last 8 tests were performed on 2 piles jacked at different spacings to study the interaction between two piles during jacking, static and cyclic loading (see Table 1). The location of the first unloaded (already installed) pile was at a distance 3d (d = pile diameter) from the centre of the vessel for all tests, and the minimum pile spacing was 3d.

Interaction During Jacking

Typical results for the jacking force of four piles jacked in different sand densities under two different overburden pressures are shown in Figure 2. The ratio of the jacking force between two consecutive piles (ie. 2nd to 1st pile, 3rd to 2nd pile and 4th to 3rd pile) appeared to decrease. This rate of decrease became more pronounced with increasing sand density. This effect can be attributed to changes in the density of the soil between the piles due to jacking of the piles becoming less significant as more piles are installed.

Figure 3 shows the influence of the number of jacked piles on the head movements of the 1st jacked pile for four tests (4PDC1, 4PDC2, 4PDC3 and 4PDC4). The overburden pressure and density for each test is shown in Table 1. The main features observed from this figure are:

a) The unloaded 1st pile jacked in medium dense sand moved downward when the 2nd pile was jacked. The 1st pile continued moving downward during jacking of the 3rd and 4th piles, with a decreased movement rate.
b) A larger movement occurs for a higher overburden pressure.
c) The first-installed pile in *dense* sand moved upward as the next

Table 1 Results from Interaction Tests Between Two Piles

Test No.	Value of Density (kN/m³)	Density	Cyclic Displac. (mm)	Over-burden Pressure (kPa)	Number of Cycles	Spacing Between Two Piles *	Vertical Deflection During Jacking (mm)	Vertical Deflection During Cyclic Loading (mm)	Max. Load Along Unloaded Pile from Jacking (N)	Max. Load Along Unloaded Pile from Testing (N)
Int-1	10.20	Med. Dense	1.25	100	100	3d	-0.23	-0.25	120.0	40.0
Int-2	10.40	Med. Dense	2.50	100	82	3d	-0.29	-0.36	116.0	51.0
Int-3	10.10	Med. Dense	1.25	200	100	3d	-0.42	-0.30	174.0	62.0
Int-4	11.50	Dense	2.50	100	100	3d	0.12	-0.41	140.0	-
Int-5	11.40	Dense	2.50	200	100	3d	0.14	0.33	234.0	98.0
Int-6	10.00	Med. Dense	2.50	200	100	4d	-0.18	-0.19	145.0	67.0
Int-7	11.30	Dense	1.25	100	100	4d	0.06	-0.14	54.0	-
Int-8	10.40	Med. Dense	2.50	200	100	5d	-0.08	-0.09	49.0	-

*d = Pile diameter

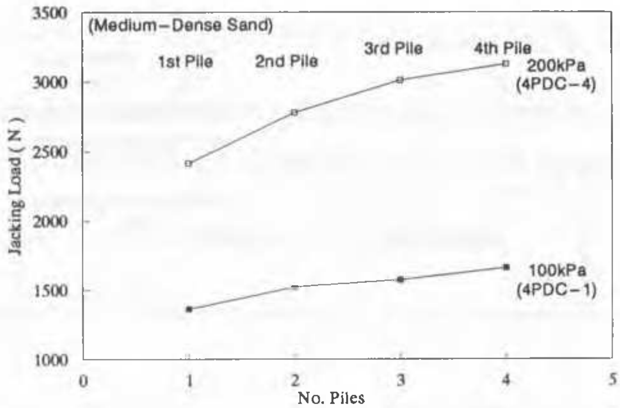

Figure 2 Number of Piles vs Jacking Load (Medium−Dense Sand)

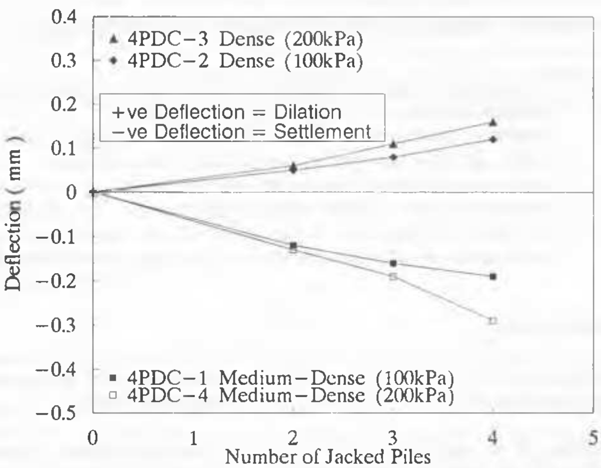

Figure 3 Influence of Number of Jacked Piles on Vertical Deflection of Unloaded (1st Jacked) Pile

pile was jacked and it continued moving upward with each successive jacked pile.

From Figure 3, it can be seen that the *direction* of the deflection (either upward or downward) is significantly influenced by the initial sand density, and the *magnitude* of the deflection is influenced by the overburden pressure.

Further results from the tests on two piles jacked in sand of different densities at different spacings show that for the lower sand density, the deflection of the unloaded (already-installed) pile after jacking the pile at 3d spacing is greater than that at 4d, but there is very little deflection of the unloaded pile after jacking the pile at 5d spacing. In all cases for dense sand, the direction of deflection is up ward.

The load mobilized along the instrumented pile during jacking of the new adjacent pile at spacing 3d has been measured by strain gauges in the instrumented pile.

Typical results for medium dense sand subjected to 100 kPa overburden pressure are illustrated in Figure 4. The maximum load is developed between the middle and bottom part of the pile, and not at the tip. The maximum load decreases as the spacing increases, reflecting the smaller interaction between the two piles. Also, the maximum load increases as the overburden pressure increases, because of the increased skin friction developed between the newly jacked pile and the soil.

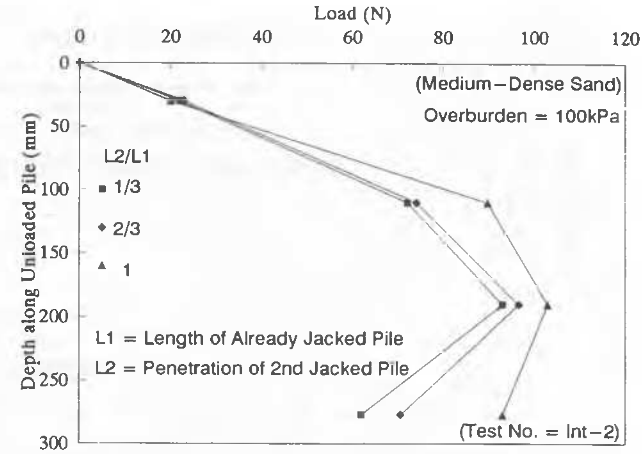

Figure 4 Typical Load Generated in Already−Jacked Pile When Jacking 2nd Pile

Interaction During Static and Cyclic loading

Figure 5 shows the experimental relationship between the deflection of an already jacked unloaded pile and the deflection of newly installed pile subjected to static tensile loading for tests Int4 and Int5. Dense sand was used in these two tests, with overburden pressures of 100kPa and 200kPa. The deflection of the unloaded pile increases with increasing deflection of loaded pile, but at a reducing rate after an initially linear relationship.

From this initial (more-or-less elastic) phase of behaviour, the settlement interaction factor can be obtained, and is found to be almost 0.17 for test Int-4 (σ_{ov} = 100kPa) and 0.09 for Int-5 (σ_{ov} = 200kPa). Clearly, the interaction factor (see Equation 1 below) decreases as deflection of the loaded pile increases and the pile response becomes increasingly non-linear. The deflection of the pile head increases as the s/d ratio decreases.

Cyclic loading also causes additional displacement of the adjacent pile. The pile head deflection increases as the cyclic displacement increases, and as the number of loading cycles increases. Figure 6 shows an example of the effect of number of cycles on the deflection of the unloaded pile, from a test conducted on medium dense sand. The highest rate of deflection occurs in the first 20 cycles and then the rate reduces.

After 100 cycles, the additional deflection of the adjacent pile is about 24% of the cyclic displacement imposed on the loaded pile.

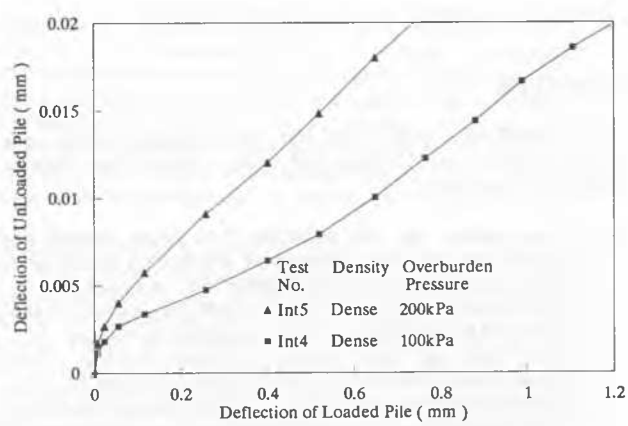

Figure 5 Deflection of Unloaded Pile vs Deflection of Loaded Pile

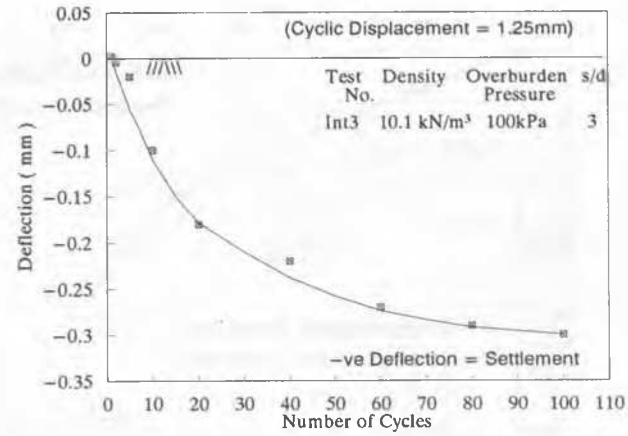

Figure 6 Number of Cycles Versus Deflection of Pile Head

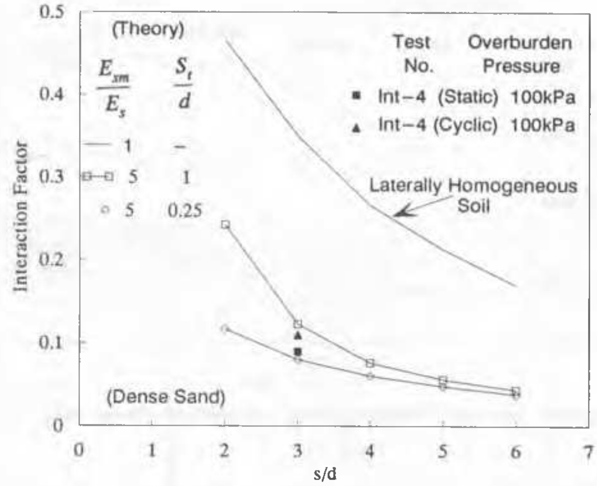

Figure 7 Measured and Predicted Interaction Factors

THEORETICAL ANALYSIS

A boundary element analysis for static axial response implemented in the computer program "DEFPIG" (Poulos, 1990), has been used to predict the displacement which arises from pile-soil-pile interaction. The results of this analysis can be expressed as an interaction factor α, where:

$$\alpha = \frac{\textit{Extra settlement caused by loading of adjacent pile}}{\textit{Settlement of pile under it's own load}} \quad (1)$$

To allow for the effects of strain-dependency of the soil modulus, the "near-pile" soil modulus (E_s) is assumed to be degraded due to pile jacking. The soil modulus in the mass of soil between the two piles (E_{sm}) will be greater than near the piles because of the smaller strain levels existing there (Poulos, 1988b). Consequently the interaction factor produced in this case is lower than for the case where the soil stiffness between the piles is constant. This phenomenon can be considered in this analysis, and it is specified by the following parameters: a) the ratio of the mass soil modulus to near-pile soil modulus E_{sm}/E_s for vertical loading, and b) the "transition distance" (s_t) over which the soil modulus changes from the "near-pile" value to the "mass" value.

Figure 7 shows the measured values of α for static and cyclic loading (for a cyclic displacement of 2.5mm), together with the predicted α for E_{sm}/E_s = 5 and s_t/d = 0.25 and 1.0. The measured α values lie between these two theoretical predictions. However, if a laterally homogeneous soil (E_{sm}/E_s = 1) was assumed, the theory would predict a significantly greater settlement interaction factor (about 0.35 for s/d = 3). Consequently the settlement of a group of piles in calcareous sand could be seriously overestimated if such an assumption was made.

CONCLUSIONS

From the model tests carried out to study the interaction between piles during installation, static loading and cyclic loading, the following conclusions can be drawn:

1) During jacking, the head deflection of an already-installed pile increases with increasing numbers of subsequently jacked piles, and also increases as the relative spacing "s/d" decreases.
2) The direction of movement of the adjacent pile depends on sand density and the magnitude depends on overburden pressure.
3) During static and cyclic loading, the head deflection of the unloaded pile increases with decreasing spacing between the piles. The influences of the sand density on the direction of deflection of the unloaded pile, and of overburden pressure on the magnitude of the deflection, are similar to those observed during jacking.
4) The maximum value of induced load in a pile due to loading of an adjacent pile occurs in the lower part of the pile.
5) Settlement interaction between two piles in calcareous sand is small, and decreases with increasing loaded pile settlement.
6) Accurate prediction of interaction requires recognition that the soil between the piles is stiffer than near the pile face. The assumption of lateral homogeneity of the soil will lead to a significant overestimate of interaction effects, and hence of group settlement.

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