Model studies of expanding piles in uncemented calcareous sand

Études du modèle des pieux en expansion dans sable calcaires

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ABSTRACT: Piles driven into calcareous, and other compressible sands generally mobilise low shaft resistances. By expanding the pile diameter in situ the normal stress, and hence the shaft resistance can be increased. This paper presents results from three different methods of increasing the pile diameter, two mechanical and one chemical. The mechanical methods involved the installation of close fitting sleeves over an existing pile, and the expansion of a thin walled membrane. The chemical method involved the use of quicklime. Details of the design and procedure for the three types of model pile are presented. Increases in shaft resistance of up to eight times were measured for a diametral expansion of 10%. Results from load tests on the different piles are presented and reasons for differences in the effectiveness of the expansion are discussed.

RÉSUMÉ: Pieux battus dans calcaire, et autre sables compressées généralement mobilisés efforts a l'interface sol-pieux basses. Par en expansion le diamètre des pieux le contrainte normal, et d'ici les efforts mobilisés a l'interface sol-pieux peut être augmentée. Ce papier présente des résultats de trois méthodes différentes de croissant le diamètre des pieux, deux mécanique et une chimique. Les méthodes mécaniques ont impliqué l'installation de manches proches appropriées sur un pieux existant, et l'expansion d'une membrane mince murée. La méthode de la chimique a impliqué l'emploi de chaux vive. Détails de la conception et procédure pour les trois types des pieux du modèle sont présentés. Augmente dans efforts mobilisés a l'interface sol-pieux de jusqu'à huit temps pour une expansion du diamètre de 10% a été mesuré. Résultats des pieux différents sont présentés et raisons pour différences dans l'efficacité de l'expansion sont discutées.

1 INTRODUCTION

Displacement piles generally mobilise significantly lower shaft friction in calcareous sediments, relative to piles driven in less compressible silica soils. In recent times recognition of this problem has often led to the abandonment of displacement piles in favour of the far more expensive, yet more effective, drilled and grouted pile. Calcareous soils originate predominantly from the remains of marine organisms, and are typically composed of highly angular, relatively weak soil particles, that are arranged in relatively open, high void ratio soil matrices. The basis for the low shaft friction mobilised by displacement piles in these soils is discussed by Poulos (1999), who reviewed the findings of several researchers. Poulos states that whilst crushing of calcareous soil particles probably partially contributes to the low shaft frictions, the main reason for this phenomenon is the high void ratios of these materials, which enables them to undergo large volumetric compressions under the shear stresses imposed during installation.

Broms (1985) discussed the benefits derived from foundations formed by mechanically expanded bodies within soil. He introduced the 'expander body pile', which consisted of a thin-walled, folded steel membrane which could be inserted or driven into the soil and 'ballooned' with cement grout. Burland (1992) described an alternative mechanism for an expanding pile foundation. The 'wedge pile' he described consists of a thin walled steel skin membrane that is lowered into a pre-bored hole and expanded radially with a driven, tapered mandrel.

The enhanced shaft friction and foundation capacity derived from either driven and grouted piles, or mechanically expanded piles has now been demonstrated, at least qualitatively, for a variety of soils. However, to date, the relationship between the degree of pile shaft expansion (through radial enlargement) and the subsequent improvement in shaft friction has not been quantified in detail. The aim of this paper is to describe the results of 3 model studies aimed at providing such quantitative data for the important case of piles installed within calcareous sediments.

2 SOIL PREPARATION AND PILE DETAILS

The carbonate sand used in the model tests was obtained from a location adjacent to Esso's Kingfish 'B' platform in Bass Strait, Australia. The material can be classified as a bioclastic 'siliceous carbonate' sand. The engineering properties of Kingfish 'B' sand have been described by Hudson et al (1988) and Airey et al (1988).

The sleeved and membrane piles were load tested in uncemented carbonate sand contained within a large calibration chamber, which had overall dimensions of 1.0 m in diameter and 1.5 m in depth. These sand samples were manufactured by pluviating dry sand directly into the test vessel. Surcharge stress was applied to the top of the soil samples to simulate stress conditions beneath the mudline (refer to Table 1). A friction reducing liner was installed at the interface of the chamber wall and the sand, to ensure a reasonably uniform vertical stress profile. Kelleher (1996) gives further details of the sand preparation methodology and the calibration chamber.

The sleeved pile consisted of three main components. A 50 mm diameter, 1 m long model pile, and two close fitting sleeves. The inner sleeve had an outside diameter of 55 mm; whilst the outer sleeve had an outside diameter of 60 mm. Both sleeves were installed individually with a screw jacking mechanism. The pile head and pile tip were equipped with separate load cells to differentiate between the loads mobilised on the pile shaft and the pile tip.

The membrane pile shaft was constructed from two components. The external part of the shaft consisted of an 800 mm long sacrificial seamless copper tube, which had an outside diameter of 51 mm. The copper tube was clamped at both ends to a rela-

Table 1: Average properties of the sand samples

Dry Unit Weight (kN/m^3)	Void Ratio	Test Type and No.	Overburden Stress (kPa)
13.65	0.962	Sleeved SP100	100
13.39	1.000	Sleeved SP200	200
13.80	0.941	Sleeved SP300	300
13.77	0.945	Membrane MPUC1	200
13.68	0.958	Membrane MPUC2	200
11.46	1.34	Lime L1	50
11.73	1.28	Lime L2	100
11.5	1.33	Lime L3	200
11.5	1.33	Lime L4	400

tively rigid, inner steel shaft. The membrane could be inflated hydraulically with pressurised oil, and the average diameter determined by monitoring the volume of oil. During installation and load testing, separate load cells were used to measure the axial load applied to the pile head and the pile tip. Further details of the sleeved and membrane piles are presented by Kelleher (1996).

The testing methodology was similar for both types of mechanically expanded piles. Initially, the model pile was installed into the carbonate sand sample by jacking. The model pile was then cycled over a single, large displacement cycle to assess the mobilised shaft friction prior to expansion. All load cycling was undertaken at a displacement rate of 0.5 mm/sec. The pile diameter was then expanded. For the sleeved pile this involved screw jacking a sleeve over the installed pile, and mechanically clamping the two components at the pile head. Expansion of the membrane pile involved injection of a measured quantity of high pressure oil. The process of expansion and load cycling was undertaken twice for the sleeved pile, and up to 4 times for the membrane pile.

The lime piles 26 mm in diameter and 256 mm long were placed in the centre of a confining vessel having the same length as the piles and a diameter of 172 mm. The lime piles were created outside the test chamber. A thin metal disk 26 mm in diameter was threaded down a central 5 mm steel shaft, and this was placed in a split plastic tube of the same diameter. Quicklime was poured into the tube and compacted to a predetermined density. When approximately 60 mm of lime had been placed a metal disc also of 26 mm diameter was screwed down the shaft and tightened to further compact the lime. This process was repeated for the length of the pile with a final disc placed on the top of the pile. The metal discs along the length of the pile were necessary to enable the shear stresses mobilised at the pile-soil interface to be transferred to the smaller diameter steel shaft. The split tube was then removed, the lime pile placed in the test vessel, and dry sand pluviated around it. Surcharge stresses were applied to both top and bottom of the soil to ensure a uniform vertical stress profile. The soil was then saturated by applying a small head of water at the bottom of the soil specimen. After saturation at least two days was allowed to ensure that the lime had fully hydrated and expanded. The central reinforcing rod was then pulled out of the soil at a steady displacement rate of 1.5 mm/min until a displacement of about 30 mm had occurred. The chamber was then disassembled and the final diameter of the lime pile measured.

To assess the influence of the expansion the test procedure was then repeated using the already expanded lime pile.

3 SLEEVED PILE TEST RESULTS

Results of a typical sleeved pile test are presented on Figure 1. In this plot the average shaft friction is normalised against the applied overburden stress (τ/σ'_v), where positive values of τ/σ'_v generally represent compression loading of the pile. The data are plotted against normalised penetration (P/D), where P is the penetration of the pile shaft below the top of the sand sample, and D is the current diameter of the pile shaft. Note that the shift to the left of successive loops in the figure is largely due to the increase in the shaft diameter, D. Figure 2 presents the relationship between normalised peak shaft friction (τ_{pk}/σ'_v) and diametral expansion ($\Delta D/D$), during the compression phase of cyclic loading. Figure 3 presents the equivalent normalised data from the tension phase of cyclic loading.

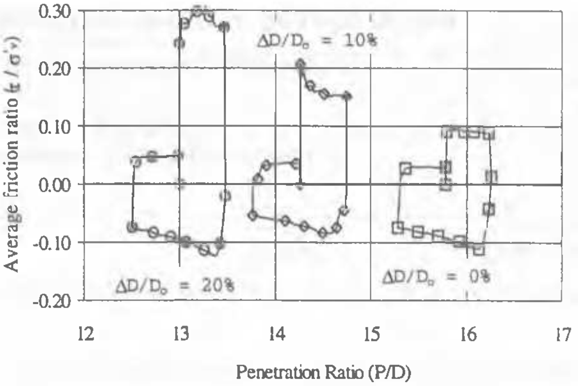

Figure 1. Average shaft friction for a typical sleeved pile test (SP200)

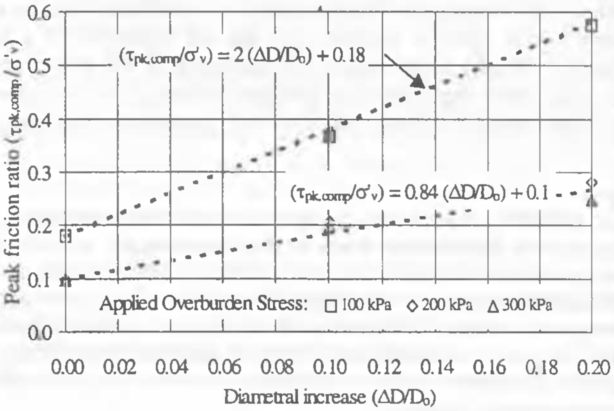

Figure 2. Peak shaft friction on a sleeved pile, compression phase of cycling

Figure 1 shows that significant increases in shaft friction can be measured during the loading after inserting the sleeve, but that when the direction of loading is reversed little benefit of the increased diameter is observed. Figures 2 and 3 show that the relationship between peak friction ratio and diametral expansion can be reasonably described using linear relationships, and that

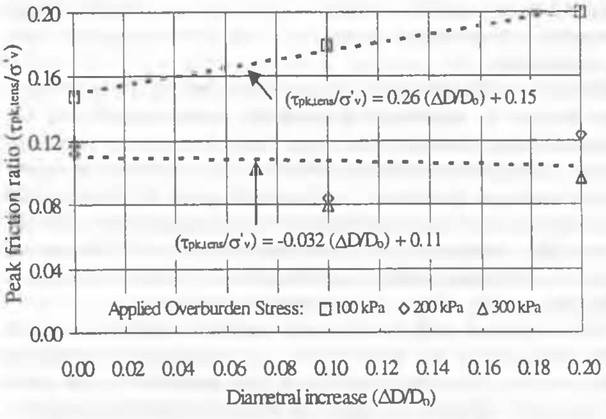

Figure 3. Peak shaft friction on a sleeved pile, tension phase of cycling

significantly greater increases in skin friction are observed at a confining stress of 100 kPa than for the higher confining stresses of 200 kPa and 300 kPa. A marginal improvement in shaft friction was measured during the tension phase of cyclic loading, under an applied overburden stress of 100 kPa. However, no discernable increase in peak friction under tensile loading was measured at higher levels of confining stress.

It was postulated that whilst the insertion of a sleeve led to some radial displacement and compaction of the soil matrix adjacent to the pile, the majority of the potential increase in radial stress associated with the increase in diameter was absorbed by volumetric collapse of the soil associated with cylindrical shearing during sleeve insertion. These perceived limitations of the sleeved pile led to the development of the membrane pile, which was capable of expansion without inducing cylindrical shearing of the soil.

4 RESULTS OF THE MEMBRANE PILE TESTS

In all cases, the skin friction mobilised following expansion of the membrane pile's shaft was found to be much greater than the value measured immediately after installation, and much greater than for the sleeved pile. The relative improvements in-shaft friction are evident on Figure 4, at increasing shaft diameters. The axial load on the pile was cycled immediately following installation by jacking, then at four separate diametral increases of 2.1, 6.3 and 11.4%. In this test, the pile shaft ruptured as the diameter was increased to 15%.

Increases in the measured shaft friction resulting from the increased diameter were very pronounced. Figures 5 and 6 illustrate the peak friction ratios measured during the initial forward (compression) and reverse (tension) phases of cyclic loading, respectively. The peak friction ratios were observed to increase eightfold (from less than 0.1 to at least 0.8) following an average diametral increase ($\Delta D/D_o$) of 11.3%. Remarkably consistent results were obtained from the two tests. As for the sleeved pile, the relationships between peak friction ratio and diametral increase could be reasonably described by linear relationships. Lines of best fit, excluding data where the membrane had ruptured, are included on Figures 5 and 6. The results also show a significant improvement in the residual frictional capacity following expansion. In all cases, severe degradation in the shaft friction was observed during the second compression phase of cyclic loading, in which the peak friction ratio (τ_{pk}/σ'_v) only reached 0.18 despite an increase in diameter of 11.4%. This behaviour, which is exacerbated by the small pile diameter, is attributed to shearing and collapse of the soil structure due to the large shear displacements, combined with multiple reversals of loading direction (Lee and Poulos, 1987).

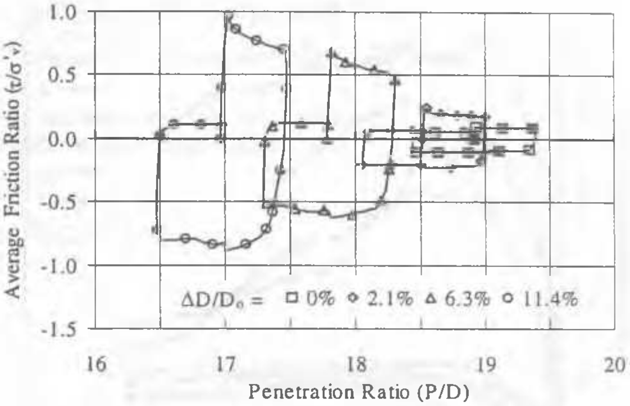

Figure 4. Average shaft friction for a typical membrane pile test (MPUC1)

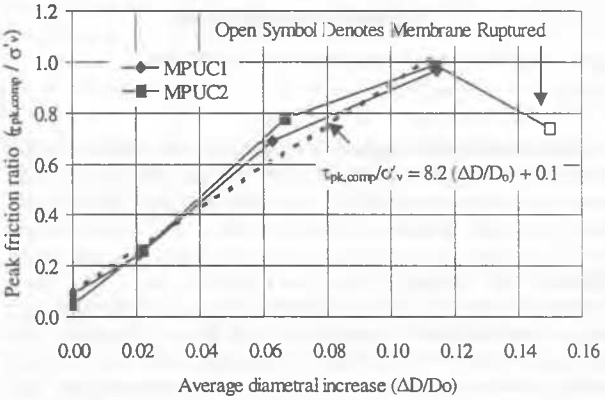

Figure 5. Peak shaft friction on a membrane pile, compression phase of cycling

5 RESULTS OF LIME PILE TESTS

Figure 7 shows the results from the lime pile tests, plotted as the average mobilised friction ratio (τ/σ'_v), versus displacement normalized by pile diameter (s/D). More details of the lime pile tests are given by Blake (1998) and Lee (1999). The tests in which the lime piles expanded following saturation (indicated by the open symbols) show significantly higher peak resistances, up to 4 times higher, than the same piles when they were retested. It can also be seen from this figure that the peak mobilised friction ratio for the expanded piles decreases as the confining pressure increases, whereas the pre-expanded piles show little effect of confining pressure. As a result the increase in the normalized friction ratio decreases with confining pressure, dropping from 4 times at 50 kPa to 2 times at 400 kPa. The diametral expansion ($\Delta D/D_o$) of the lime piles varied from 35% to 50% with a slight trend towards lower expansion at higher confining stress. The increase in the peak friction ratio of the lime piles of 4 times for a diametral expansion of 50% is considerably less than for the membrane pile, which increased over 8 times for an expansion of 10%. Possible reasons for the different behaviour are considered below.

The increase in normal stress acting on the pile after expansion is affected principally by the stiffness of the surrounding soil, and the amount of expansion. Both of these are affected by the stress state in the soil. It can be seen from Table 1 that the sand specimens used in the membrane pile tests were significantly denser. It would therefore be expected that a given expansion of the membrane pile would result in a greater increase of normal stress on the pile and hence a greater frictional resistance. For the lime piles it was also expected that the amount of expansion of the lime would be related to the confining pressure as reported by Chun et al (1997). Figure 8 shows the results

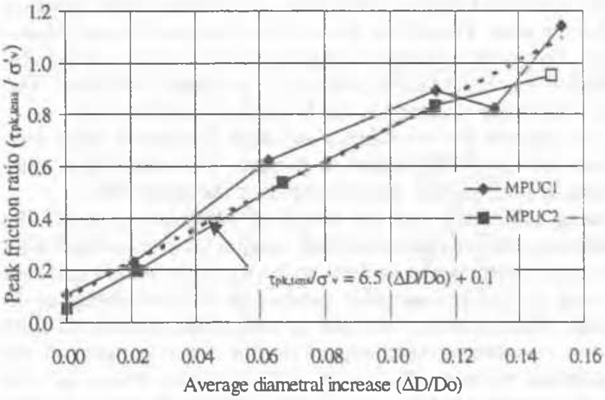

Figure 6. Peak shaft friction on a membrane pile, tension phase of cycling

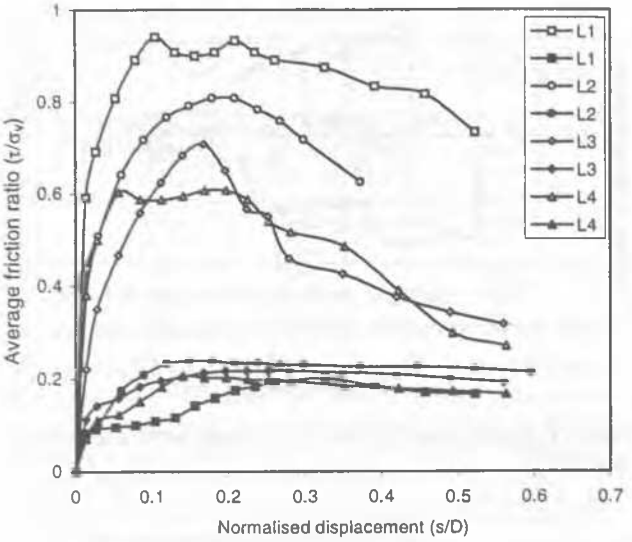

Figure 7. Shaft frictions measured in lime pile tests

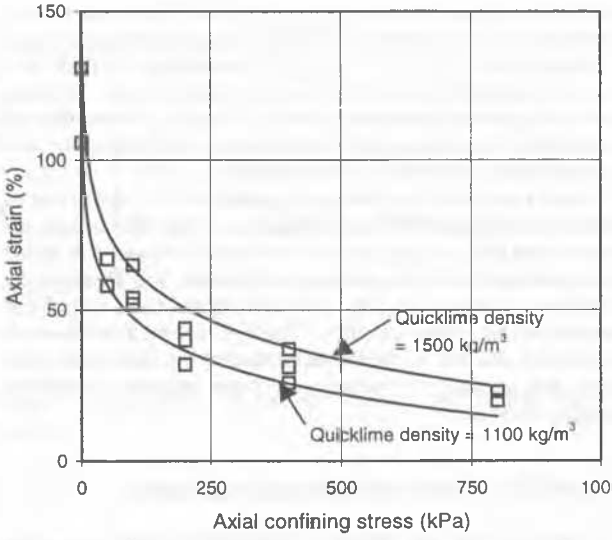

Figure 8. Quicklime expansion on hydration in oedometer tests

from oedometer tests designed to investigate the effects of stress and quicklime density. In these tests dry quicklime was compacted in an oedometer and an axial stress applied. The axial expansion was then measured as water under a small head was applied at the base. It was found to be important that the initial thickness of the oedometer specimens was less than 10mm, for a diameter of 55mm, to avoid significant frictional stresses developing on the sides of the oedometer, and giving apparently low expansions. Figure 8 shows that increases in confining stress and decreases in density of the lime result in reduced expansion, and that the reduction in the amount of expansion is relatively rapid at low confining stresses.

Very high stresses are required to completely prevent expansion as a fully confined specimen of quicklime mobilised an axial stress of 15MPa and a radial stress of 10 MPa on saturation.

As a consequence of the greater expansions observed at low confining stresses in the oedometer tests and the lower stiffness of soil at lower stresses, a significantly greater expansion of the lime piles was expected at lower stresses. However, only a slight decrease in the amount of expansion was measured for confining stresses up to 400 kPa, and volumetric expansions of 80% to 114% were measured for the piles, greater than expected from the oedometer tests, suggesting possible limitations of the oedometer test as a means of investigating the expansive nature of quicklime.

6 CONCLUSIONS

Three alternative types of expanding model piles were tested in carbonate sand. Two of the model piles (Sleeved Pile and Membrane Pile) were expanded using mechanical means, whilst the third pile was expanded by hydrating quicklime (Lime Pile). The following major conclusions can be drawn from this work.

The sleeved pile provided a threefold increase in shaft friction following a 20% increase in diameter. The relatively low increases in shaft friction were attributed to the cylindrical shearing associated with the diametral expansion process. The membrane pile provided a tenfold increase in average shaft friction under compression loading, following a diametral expansion of about 11%. The lime piles gave up to a 50% increase in diameter. This expansion resulted in a fourfold increase in shaft friction. Oedometer tests suggested that the expansion of the lime would reduce significantly with confining stress, but this was not observed in the pile tests for confining stresses up to 400 kPa.

The membrane pile is apparently more effective in increasing the shaft resistance than the lime piles, however this maybe a consequence of the lower soil density used in the lime pile tests.

The results demonstrate that, irrespective of the method used and the density of the sand, very significant increases in pile capacity are possible following radial expansion of the pile shaft.

ACKNOWLEDGEMENTS

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