# Influence of Soil Density on Pile Skin Friction in Calcareous Sediments

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SUMMARY Model tests on jacked piles in calcareous sand have been performed to study the influence of density on the shaft friction under static and cyclic loading.
Two types of test vessel have been used, in which dense and medium dense samples of New North Rankin calcareous sand have been consolidated under various overburden pressures. Model instrumented piles have been jacked into the sand samples and a study made of the influence of the sand density on the following aspects:
a) the jacking force required to install the pile
b) the skin friction and soil modulus for static loading
c) the degradation of skin friction under cyclic loading
d) the skin friction of the soil following the cyclic loading.
It has been found that the initial density of the sand has a significant effect on all these aspects.

## INTRODUCTION

Previous experience from laboratory and field tests shows that the low capacity of jacked piles in calcareous sand can cause problems in the design of foundation for offshore structures. Dramatic evidence of such problems materialized in 1982 when some driven piles at the site of the North Rankin platform on the north west shelf of Australia dropped as much as 60m (about 50% of design length) under their own weight. Such experiences have stimulated subsequent investigators to perform laboratory work under a range of test boundary conditions, in order to reach a better understanding of the behaviour of piles and to develop means for making a reasonable estimation of pile capacity under both static and cyclic loading conditions. Several programs of model and field testing of piles in calcareous soils have been undertaken in the last decade (eg. Nauroy and Le Tirant, 1983; Poulos and Chan, 1986; Poulos and Lee, 1988), but a number of aspects of pile behaviour still require further investigation. One of these aspects is the influence of the density of the calcareous soil on pile response under axial loading.

This paper presents the results of static and cyclic loading tests on model piles jacked into calcareous sand samples with different initial densities, and under various overburden pressures. The following aspects of behaviour have been studied:

a) the jacking force required to install the pile
b) the skin friction and soil modulus for static loading
c) the degradation of skin friction during cyclic loading
d) the skin friction of the soil following the cyclic loading

## PROPERTIES OF CALCAREOUS SAND

The calcareous sand used in the tests was obtained from the site of the North Rankin gas platform on the North West shelf of Western Australia. The grading curve is shown in Figure 1 and this soil can be considered to be a well graded carbonate sand of mainly bioclastic and pelletal origin. The minimum and maximum dry densities of the test samples were 9.6 kN/m$^3$ and 13 kN/m$^3$. Microscopic examinations conducted on the calcareous sand showed that it contained a diverse range of particles with a high incidence of intra-particle voids, thin-wall particles and rod-like particles (Allman 1988). The angular nature of particles of this calcareous sand lead to a high friction angle and a high void ratio, and consequent high compressibility (Hull et al, 1988). The latter reference gives typical values of parameters for calcareous sand, as shown in Table 1.

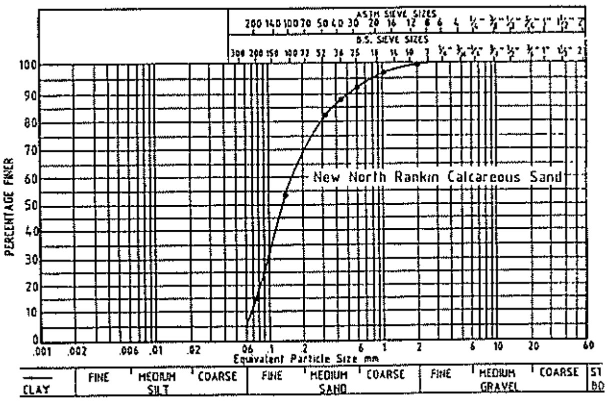

FIG 1 GRADING CURVE FOR CALCAREOUS SAND

## APPARATUS AND TEST PROCEDURE

Two different sizes of test vessel were employed in this study, to gain a better understanding of the influence of the boundary condition of the test vessel (ie. the friction between the soil and the vessel wall) on the behaviour of the pile. The details of the large

TABLE 1. Physical Properties of New North Rankin Calcareous Sands tested (Hull et al 1988)

| Cu =d10/d60 | Fineness Modulus | Carbonate Content (%) | Max. Dry Density (kN/cu.m) | Min. Dry Density (kN/cu.m) |
|---|---|---|---|---|
| 2.27 | 1.85 | 94 | 12.1 | 8.64 |

vessel and associated apparatus are shown diagrammatically in Figure 2. Both vessels were similar and in each case, it was possible to employ three alternative base conditions:

1. Rigid base: the test vessel base was a thick steel plate. This was commonly used for model pile tests in soil consolidated by a pressure applied only at the top.
2. Semi-Rigid base: in this case the soil was separated by a rubber membrane from the underlying pressurised water, which was deaired and confined in the bottom chamber. Again the soil was consolidated by an applied pressure at the top only.
3. Pressure Controlled base: This base was as for the second case, except that pressure was also applied at the bottom. In this case the soil was subjected to equal pressure at the top and base boundaries.

The tests described in this paper were obtained primarily using the rigid base and semi-rigid base conditions. The influence of the base condition was found to be relatively small, but is discussed in detail by Al-Douri (1992).

The main difference between the two vessels was that the small one had a diameter half that of the larger vessel. The large pressure vessel was mounted on a trolley which could be moved across the loading frame, permitting the model pile to be positioned for testing easily, while the small vessel was fixed on the base of the loading frame after it was positioned. The inside walls of both vessels were lined by a stainless steel sheet to reduce the friction between these walls and the sand.

The model pile was fabricated from 25mm external diameter aluminium tube, with a 3mm wall thickness. The pile was instrumented inside at 5 sections along the aluminium shaft. In each section, four electrical resistance strain gauges (forming a full Wheatstone Bridge circuit) were installed to enable measurement of the axial pile loads.

Installation and loading tests were performed by means of a loading machine of 15kN capacity. The applied load and the force along the pile were measured by a calibrated proving ring and strain gauges. The pile head displacement was measured by a displacement transducer (LVDT). All these measurements were recorded using a micro-computer connected to a data acquisition system.

The sand bed was prepared by raining sand into each vessel using a special device (Al-Douri et al 1990). The adopted procedure of raining sand produced a uniform bed of soil and enabled control of the density, with "loose" and "medium dense" sand samples being produced depending on the height of sand raining. The corresponding range of dry unit weight was 9.6 kN/m$^3$ to 10.5kN/m$^3$.

Dense samples were prepared by the same method as the medium dense, except that after raining, the soil was vibrated by two vibrators attached to the large

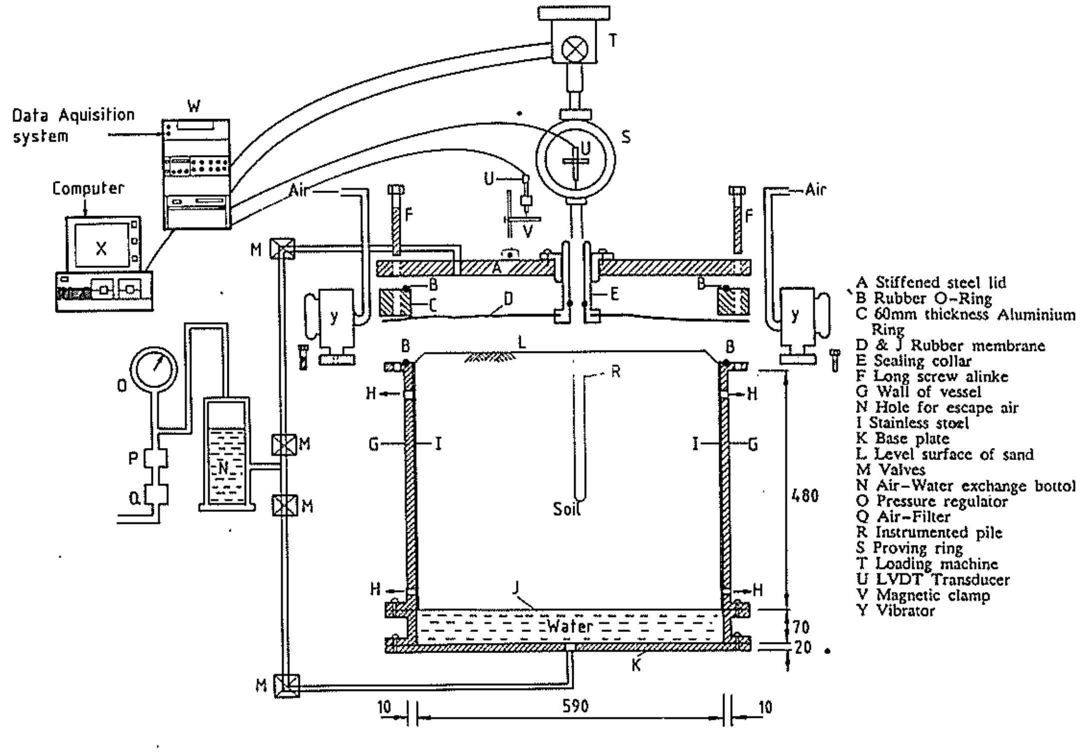

FIG. 2 DIAGRAMMATIC VIEW OF TEST SETUP

test vessel and by one on the small vessel. A unit weight greater than 10.5 $kN/m^3$ was obtained, the actual value depending on the time of vibration.
After placement of the sand, a uniform overburden pressure was applied and the soil was allowed to consolidate for a period of at least 36 hours.

At the completion of consolidation, the pile was jacked into the sand bed using a loading machine. Readings of force and displacement were taken, and the strain gauges were monitored to determine the distribution of force along the pile at various stages of the jacking process. The applied load was recorded at a specified intervals until the pile reached its final penetration of about 290mm. After jacking, the pile was left unloaded for more than three hours until the readings of the strain gauges had stabilized. After taking the final set of residual load readings, the pile was attached to the loading machine and tested.

Each test generally consisted of three stages:

1. An initial static loading, in tension, to 10% of pile diameter, which was assumed to be failure (Kulhawy and Carter 1988 ).
2. A cyclic loading of the pile between pre-determined amplitudes of displacement for between 50 to 100 cycles.
3. The final static loading, to failure, to investigate the influence of cyclic loading on the performance of the pile.

The rate of displacement was constant for all the tests at 0.4mm per minute to avoid rate of loading effects on the pile capacity response. Two series of tests were performed on piles in medium dense and dense soils, using large and small test vessels, and the results are presented below.

RESULTS

A total of 30 tensile static and cyclic tests were performed on jacked model piles using both small and large vessels. The initial density and the overburden pressure applied in the tests are shown in Table 2, which also summarizes some of the key measurements of pile behaviour.

Behaviour During Jacking

Figure 3 shows a typical result for the behaviour of an instrumented pile during jacking in dense and medium-dense samples under three different overburden pressures.

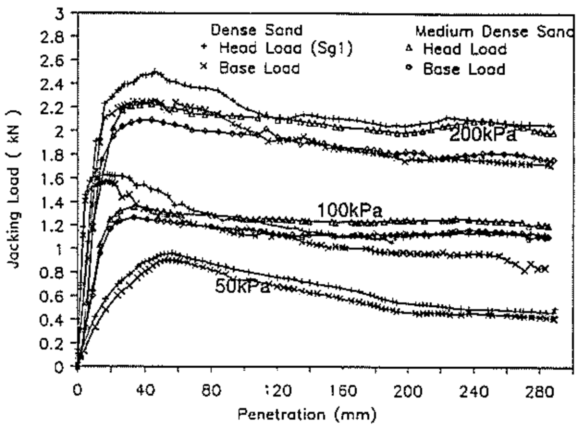

Figure 3. Head and Base Loads Versus Pile Pentration For Different Densities and Overburden Pressure

TABLE 2. Summary of Tests Carried out in Both Small and Large Test Vessels

| Vessel Type | Vertical Pressure kPa | Density Range kN/cu.m | No. of Tests | Average Maximum E.B.C * During Jacking kPa | Average Maximum Friction During Jacking kPa | Average Maximum Friction During Testing kPa |
|---|---|---|---|---|---|---|
| Small | 100 | 9.7-9.9 | 2 | 3400 | 22.1 | 9.5 |
| | 100 | 10.9-11.6 | 2 | 3528 | 32.0 | 15.4 |
| | 200 | 10.2-10.4 | 2 | 4945 | 34.8 | 22.5 |
| | 200 | 11-12 | 3 | 7478 | 47.8 | 36.1 |
| Large | 50 | 10.2 | 1 | 1854 | 12.7 | 4.0 |
| | 75 | 9.9 | 1 | 2489 | 13.6 | 4.6 |
| | 100 | 9.7-10.1 | 6 | 2857 | 18.3 | 8.3 |
| | 100 | 11-12 | 4 | 3356 | 28.6 | 14.2 |
| | 150 | 9.7-10.0 | 2 | 3315 | 21.2 | 12.0 |
| | 200 | 9.9-10.1 | 4 | 4151 | 27.6 | 16.9 |
| | 200 | 10.5-11.1 | 3 | 4866 | 33.8 | 25.9 |

* E.B.C = End-Bearing Capacity

The jacking force versus penetration for both densities increased to a peak and then decreased towards an ultimate value. The peak load was well defined for dense sand samples. The "strain- softening" behaviour appears to be more pronounced for the low overburden pressure of 50kPa than for the higher overburden pressures of 100kPa and 200kPa. The maximum values of head load and end bearing capacity for dense samples were higher than those for the medium dense samples, as can be seen from the values summarized in Table 2.

Figures 4a and 4b show the influence of soil density on the peak skin friction and end bearing resistance, normalized with respect to overburden pressure, during jacking of the piles. Both increase with increasing density as would be expected. The results are consistent with those of Poulos and Chua (1985), who observed that, for shallow foundations, the bearing capacity increased with increasing relative density of the silica and calcareous sands. However, there was a distinct tendency for the results obtained from the tests in the small vessel to be higher than those from large vessel. This reflects the greater influence of side restraint in the small vessel, especially on the skin friction.

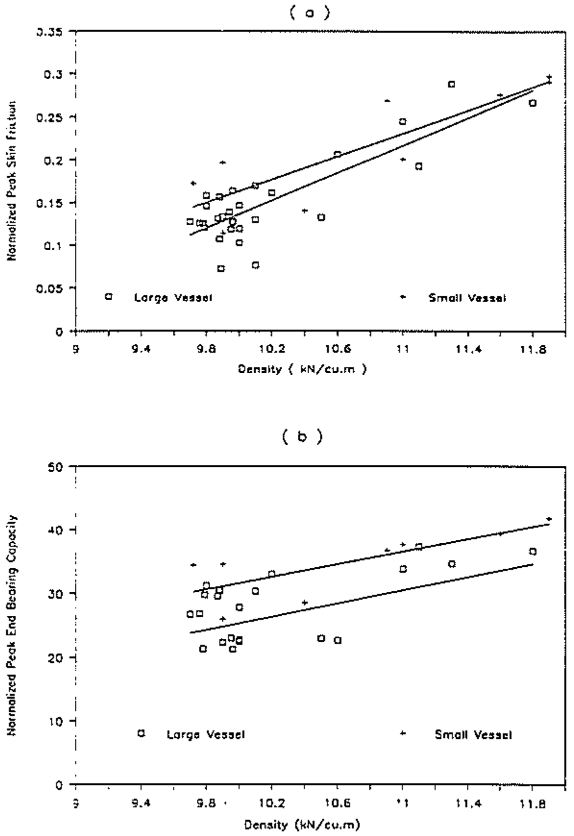

Figure 4. The Influence of Soil Density on Normalized Peak Skin Friction and End Bearing Capacity During Jacking

## Results of Static Loading Tests

Figure 5 shows typical relationships between load and deflection during tensile loading for dense and medium-dense sand subjected to 100 kPa and 200 kPa overburden pressure. For dense sand, the tensile load increased to a peak at about 0.5 mm deflection and then dropped to an ultimate value. In the case of the medium-dense sand, the load increased to a maximum value, with little evidence of a subsequent reduction.

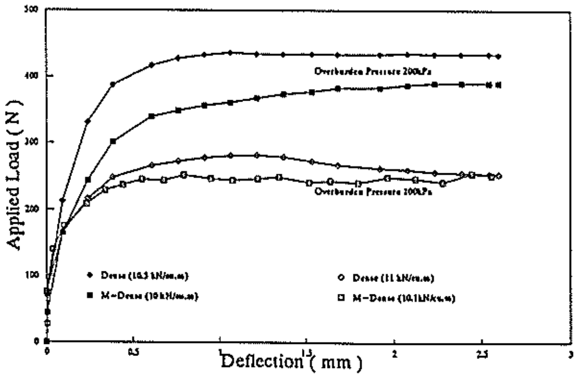

Figure 5. Load-Deflection Curves During Static Loading for Different Densities and Overburden Pressures

Figure 6 plots the peak skin friction $f_s$ as a function of applied overburden pressure $\sigma'_{vo}$, and reveals a reasonably linear relationship. The values of $f_s$ are lower than those for piles in silica sands. Expressing the normalized static skin friction as $f_s/\sigma'_{vo}$, Figure 7 shows the influence of density on $f_s/\sigma'_{vo}$ obtained from tests using both small and large vessels. The normalized skin friction in both cases increases with increasing density, but the values from small vessel tests tend to be greater than those from the large vessel, again apparently reflecting the influence of lateral restraint. The values of normalized skin friction in Figure 7 are lower than those recorded during jacking (Figure 4a), but the reason for this difference is not clear at the present time.

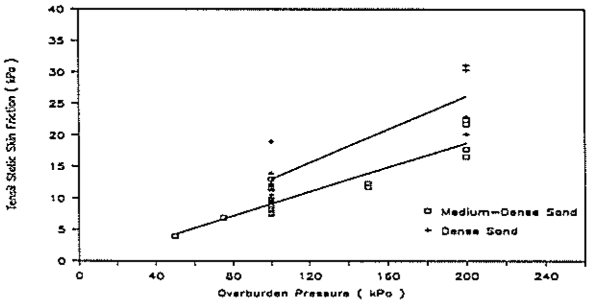

Figure 6. The Influence of Overburden Pressure on Static Skin Friction For Medium-Dense and Dense Sands

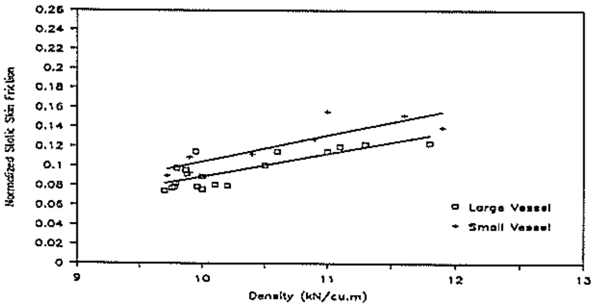

Figure 7. The Influence of Soil Density on the Normalized Static Skin Friction Using Both Large and Small Vessels

From the load-settlement behaviour, the initial slope may be used with the elastic theory of Randolph and Wroth (1978) to backfigure the equivalent Young's modulus of soil.

Figure 8 shows the initial tangent soil modulus $E_t'$ versus effective overburden pressure for both medium-dense sand and dense sand. The value of $E_t'$ increases as $\sigma_{vo}'$ increases, and is substantially greater for the dense sand than for the medium-dense sand. Corresponding values of Young's modulus $E_{50}'$, for a load level of 50% of ultimate, are shown in Figure 9. Again $E_{50}'$ increases with increasing overburden pressure in both medium-dense sand and dense sand, and is smaller than the tangent value $E_t'$. The $E_{50}'$ values from the present tests are similar to those obtained by Allman (1988) using a vessel similar to the small vessel used here.

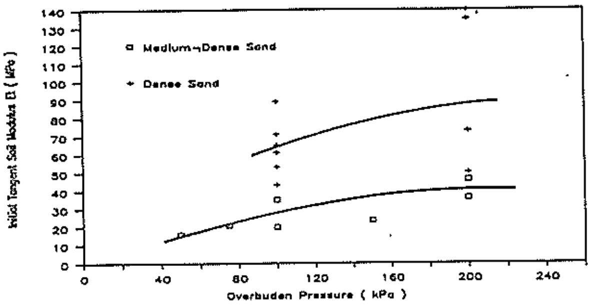

Figure 8. Effect of Overburden Pressure on Initial Tangent Soil Modulus for Medium-Dense and Dense Sands

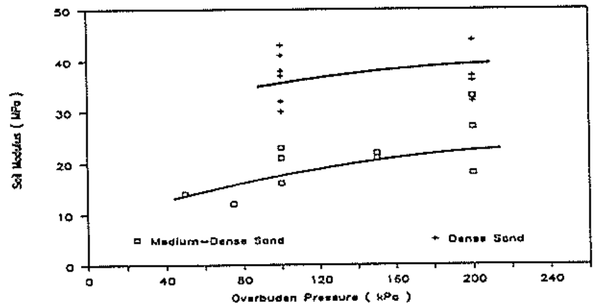

Figure 9. Effect of Overburden Pressure on the Static Young's Modulus "E50" for Medium-Dense and Dense Sands

## Results of Cyclic Loading Tests

The skin friction degradation factor $D_f$ is defined as the ratio of post-cyclic skin friction $f_c$ to the peak static skin friction $f_s$. The influence of density on the magnitude of degradation factor is demonstrated in Figure 10. Figure 10a shows the relationship between the $D_f$ and number of cycles in both medium-dense sand and dense sand for a given $\sigma_{vo}' = 100$kPa and a cyclic displacement $\pm\rho_c = 1.25$mm. Figure 10b shows the same relationship in Figure 10a for $\sigma_{vo}' = 200$kPa and a cyclic displacement $\pm\rho_c = 2.5$mm. For all tests, the highest rate of degradation occurs in the first 10 cycles and then the rate reduces. The value of $D_f$ for medium-dense sand is greater than that for dense sand indicating that cyclic degradation is more severe for dense sand. The results of Allman (1988) on a jacked pile in dense calcareous sand are also shown in Figure 10b, and are consistent with the present results.

The variation of $D_f$ with effective overburden pressure illustrated in Figure 11. The value of $D_f$ decreases as $\sigma_{vo}'$ increases for both sand densities. These results differ from some earlier tests (Chan 1986) in which the degradation factor appeared to be more or less independent of $\sigma_{vo}'$. Chan's tests were carried out on a different calcareous soil (from Bass Strait).

The influence of cyclic displacement on the value of $D_f$ for medium-dense sand under $\sigma_{vo}' = 100$kPa and $\sigma_{vo}' = 200$kPa is shown in Figure 12. As found in previous tests, the value of $D_f$ increases as $\pm\rho_c$ increases. The values of $D_f$ for cyclic displacements of 0.5mm and 0.25mm are similar to those obtained from jacked piles in calcareous sand by Chan (1986).

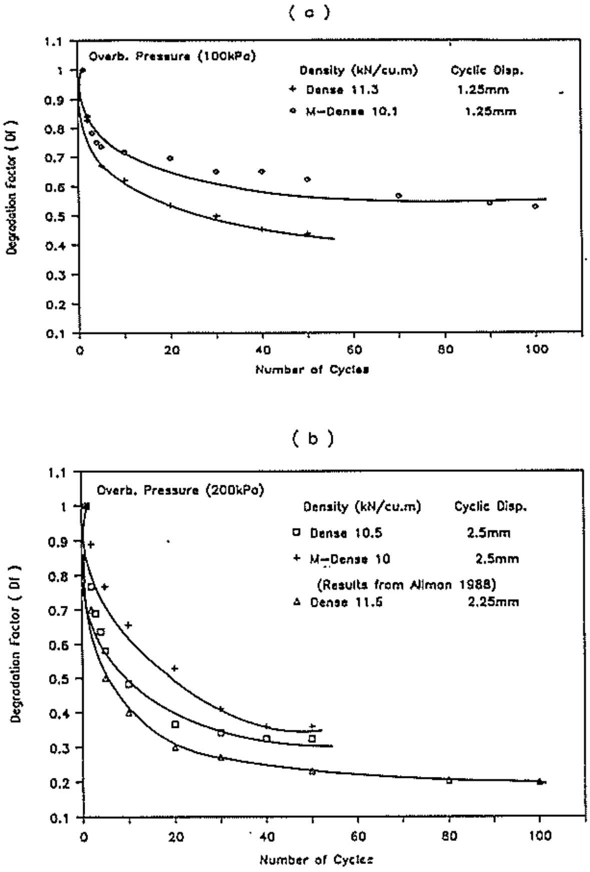

Figure 10. Degradation Factor Versus Number of Cycles

It is noteworthy that low values of $D_f$ (0.6 or less) can occur for $\pm\rho_c$ in excess of about ± 0.5 mm, ie. cyclic loading can cause a severe loss of skin friction. However, the cyclic degradation for jacked piles is not as severe as for the grouted model piles tested by Lee and Poulos (1990), for which degradation factors of less than 0.1 were obtained.

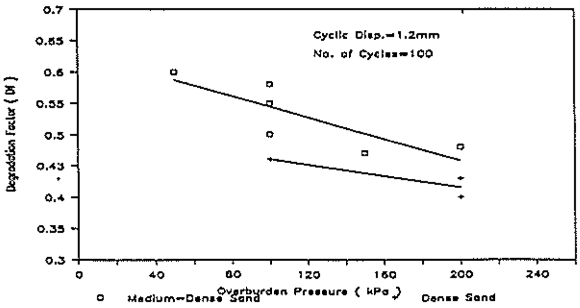

Figure 11. Degradation Factor Versus Overburden Pressure for Medium-Dense and Dense Sands

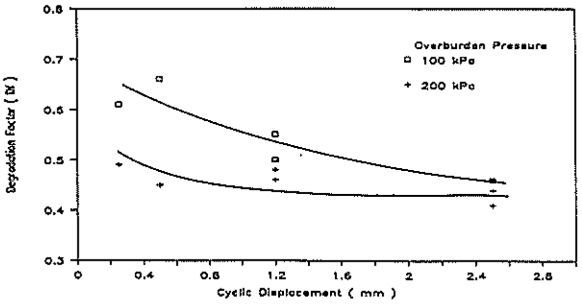

Figure 12. Degradation Factor Versus Cyclic Displacement for Medium-Dense Sands Under 100 and 200 kPa

## CONCLUSIONS

Model tests on jacked piles in calcareous sand have been carried out to investigate the influence of initial soil density on the resistance during jacking, the static skin friction and soil stiffness, and the degradation of skin friction under cyclic loading. Tests were carried out for two different density states ("medium-dense" and "dense") in two different sizes of test vessel.

The tests carried out in the smaller test vessel show generally higher values of skin resistance, indicating that the results of these tests may be influenced by the side-wall restraint of the vessel.
The following conclusion have been drawn from the tests:

1) the jacking resistance increases as the initial soil density increases, with both the end-bearing and shaft resistance increasing

2) the jacking resistance increases as the overburden pressure increases

3) both skin friction and soil Young's Modulus increase with increasing soil density and increasing overburden pressure

4) the skin friction developed under static loading conditions is less than that developed during jacking.

5) under cyclic loading, the skin friction tends to "degrade". Degradation becomes more severe as the soil density increases.

6) degradation of skin friction becomes more severe as the cyclic displacement increases and as the overburden pressure increases.

It is believed that the results of these tests are of value in the design of driven piles in calcareous sediments.

## ACKNOWLEDGEMENTS

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