Behaviour of grouted piles in offshore calcareous sand

Le comportement de pieux injectés dans un sable calcaire marin

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SYNOPSIS: Model pile tests have been performed in a specially-designed apparatus to study the stability of a pile under various combinations of mean and cyclic loads. On a cyclic stability diagram, plotting cyclic load level against mean load level, two distinct zones have been identified: a stable zone in which cyclic loading has no effect on pile capacity, and an unstable zone in which cyclic loading causes the pile to fail within a specified number of cycles. These cyclic stability characteristics found in the model tests have been compared with some field test results and found to be consistent over a wide range of load levels.

A theoretical analysis based on a simple degradation model is described, and is shown to predict the general behaviour of the model pile tests reasonably well.

1. INTRODUCTION

The skin friction of driven piles in offshore calcareous soils is low mainly due to low lateral soil pressures caused by pile driving (Lu, 1986; Murff, 1987; Nauroy et al, 1985; Poulos et al, 1986). Drilled and grouted piles offer an attractive, although more expensive alternative, and some field and laboratory tests have indicated that the static skin friction of grouted piles can be as much as seven times higher than for driven piles. However a limited number of tests have also indicated that cyclic loading can significantly reduce the skin friction developed on grouted piles (Murff, 1987; Nauroy et al, 1985).

This paper describes model pile tests which have been carried out in a specially-designed apparatus to investigate the skin friction of grouted piles in an offshore calcareous sand. Poulos and Lee (1988) have illustrated the influence of overburden pressure, relative density and over-consolidation ratio on the grouted pile static skin friction and soil modulus, and also the degradation of skin friction under displacement-controlled cyclic loading. The main objective of the tests presented here has been to examine the stability of the pile under load-controlled cyclic loading. Comparisons between these model tests and some field tests are also presented and discussed. A theoretical analysis of cyclic response, based on a simple degradation model, is then described, and the theoretical response is compared with that observed from laboratory tests.

2. EXPERIMENTAL PROCEDURE AND RESULTS

The calcareous sand used in the model pile tests was obtained from the North-West Shelf of Australia at the site of the North Rankin A platform. It consisted mainly of silt and sand size particles. The minimum and maximum densities of the sand were about 1.05 t/m³ and 1.37 t/m³ respectively. The average carbonate content was 97%. Drained triaxial compression tests showed that the drained properties of the sand could be expressed as follows (Hull et al, 1988):

$$\varphi'_{peak} = 46.8 - 0.02\,\sigma'_c \qquad (1)$$

$$E'_{max} = 7.8 + 0.32\,\sigma'_c \qquad (2)$$

in which φ'_{peak} is the drained peak friction angle, E'_{max} is the drained Young's modulus in MPa at a low strain level, and σ'_c is the effective confining pressure (in kPa) in the range of 100 to 400 kPa. The drained Poisson's ratio, ν'_{min}, at low strain levels was found to have an average value of about 0.15.

The apparatus used in the model pile tests has been described in detail by Poulos and Chan (1986) and is illustrated in Figure 1. The internal diameter of the test vessel was 180 mm and the depth 256 mm. This device was specially developed to allow the pile shaft to be installed in a soil layer which had stress-controlled end conditions, with an equal consolidation pressure being applied to both the top and bottom of the soil sample, and the sides being restrained. Consolidation is thus carried out under confined one-dimensional conditions. The model pile installation procedure has been described in detail by Poulos and Lee (1988). The dimensions of the grouted pile were measured at the completion of the test. The length of the grouted pile was typically about 256 mm while the average diameter was about 24 mm.

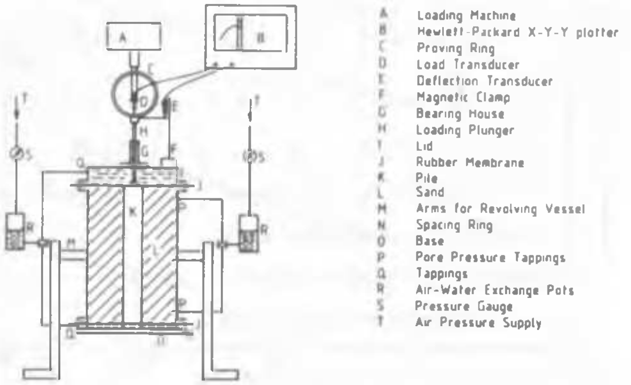

Figure 1. Experimental apparatus

For each test, the pile was initially loaded statically to a specified mean load level, then either one or two way cyclic loading, between predetermined limits of load, was applied for a specified number of cycles. Some of the piles were subjected to a final static loading test to failure after cyclic loading.

The pile was assumed to fail at a permanent displacement of 2.5 mm (i.e. 10% of pile diameter). About 28 tests were performed at various combinations of mean (P_0) and cyclic ($\pm P_c$) load. The conditions used in the tests were as follows:

Soil relative density = 56 to 63%

Effective overburden pressure = 200 kPa

Over-consolidation ratio = 1

Mean load (P_0) = 0 to 0.9 of static pile capacity P_u

Cyclic load (P_c) = ±0.05 to 0.8 of static pile capacity P_u

Number of cycles (N) = 1 to 3000.

The test results show that the permanent displacement S_p increases with increasing cyclic load level and number of cycles. Figure 2 shows that S_p can be approximately represented by the following expression, which is similar to the form used by Diyaljee and Raymond (1982) for triaxial test results:

$$S_p/d = A \cdot \exp(nX) \cdot N^m \qquad (3)$$

where S_p = permanent displacement

d = pile diameter

X = applied cyclic load level

N = number of cycles

A, n, m = experimentally-determined parameters.

From the experimental data, average values of $m = 0.28$, $n = 5.1$, and $A = 0.4$ are obtained.

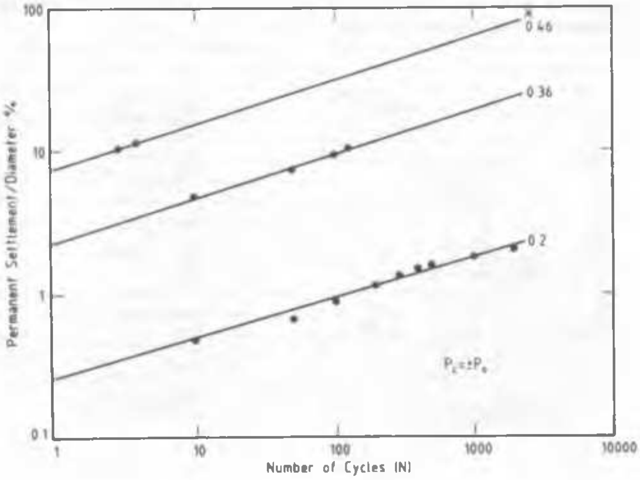

Figure 2. Development of permanent settlement with number of cycles

Poulos (1988) proposed the concept of a cyclic stability diagram for representating the general pile behaviour under cyclic loading. This diagram plots the mean load level against the cyclic load level and indicates the consequent behaviour of the pile, in particular, the combinations of mean and cyclic load which have no influence on ultimate pile load capacity (the cyclically "stable zone") and those combinations which lead to failure within a specified number of cycles (the cyclically "unstable zone"). Figure 3 shows the cyclic stability diagram derived from the model pile tests.

The following features can be noted:

(i) contours of number of cycles to cause failure are plotted on the diagram. They tend to move closer to each other with increasing mean load levels and also with decreasing cyclic load levels;

(ii) if the cyclic load level does not exceed about 20% of the static load capacity, P_u, there appears to be no loss of load capacity over a wide range of mean loads. This appears to define the cyclically stable zone;

(iii) unfortunately, there is no experimental data which can be used to define the metastable zone in which the pile suffers some limited loss of capacity, but does not fail

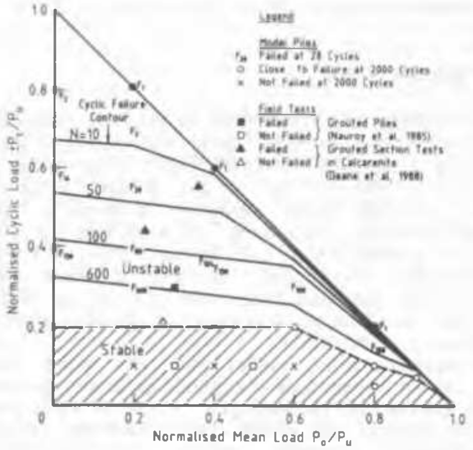

Figure 3. Cyclic stability diagram

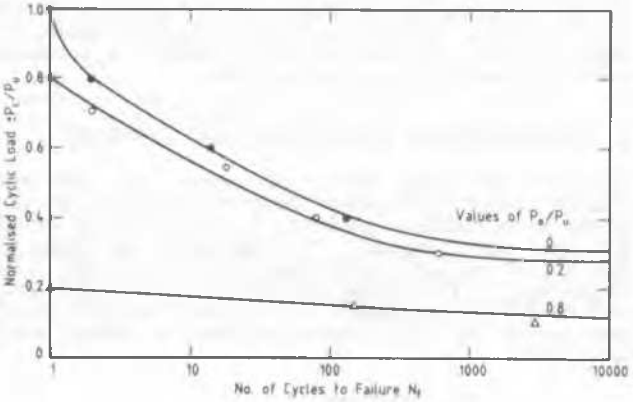

Figure 4. "Fatigue curves" for model piles

during cycling. However, there appears to be a well-defined unstable zone in which cyclic loading results in failure of the pile within a specified number of cycles.

For comparison purposes, some field test results (Deane et al, 1988; Nauroy et al 1985) are also plotted on the cyclic stability diagram and these are found to be consistent with those obtained from the model tests.

"Fatigue curves" which illustrate the relationship between cyclic load level and number of cycles to cause failure, N_f, are shown in Figure 4. It is found that as the mean load level decreases, the "fatigue curve" tends to become flatter which implies that N_f is very sensitive to cyclic load level.

Figure 5 demonstrates that the ultimate load capacity after cycling decreases due to cyclic loading. The reduction can be greater than 40% of the static ultimate capacity at high cyclic load levels. For mean load levels in excess of about 46% of P_u, failure (or reduction in load capacity), is mostly due to the rapid accumulation of permanent displacement.

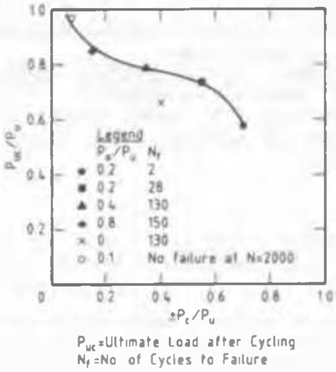

Figure 5. Effect of loading on ultimate load capacity

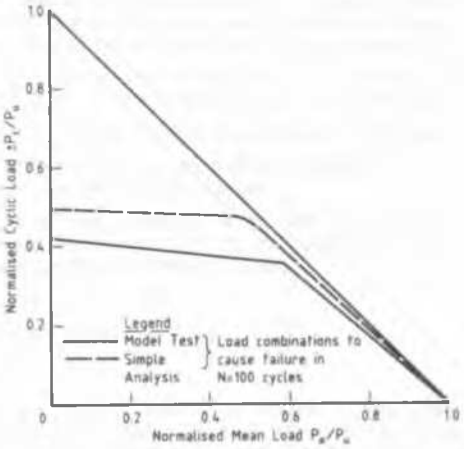

Figure 6. Comparison between cyclic stability diagram from model tests and simple analysis

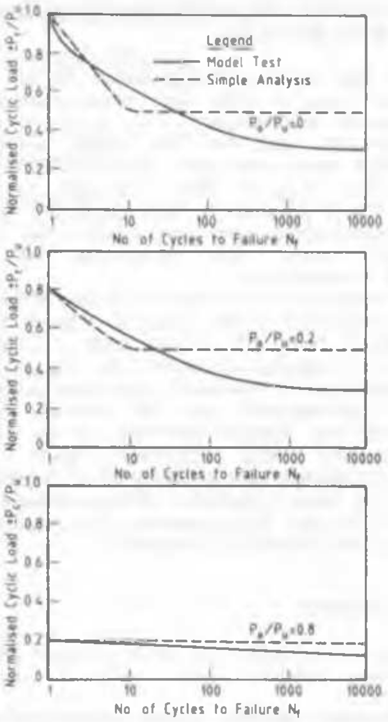

Figure 7. Comparison between "fatigue curves" in model tests and simple analysis

3. SIMPLIFIED THEORETICAL ANALYSIS

Details of an analysis for cyclic axial response are described by Poulos (1988). A simplified form of boundary element analysis is used in which the pile is represented as an elastic cylinder and the surrounding soil mass as an elastic continuum. Nonlinear and cyclic degradation effects are incorporated in the interface characteristics.The following features are considered:

(i) pile-soil slip when the shear stress reaches the current limiting value of shaft resistance;

(ii) accumulation of permanent displacement under cyclic loading; this is described by an expression similar to Equation 3;

(iii) cyclic degradation of shaft resistance; this is expressed by the simple Matlock and Foo (1979) model:

$$D_\tau = (D_\tau' - D_{\tau lim})(1 - \lambda) + D_{\tau lim} \qquad (4)$$

where D_τ = current value of degradation factor

D_τ' = degradation factor for previous cycle

$D_{\tau lim}$ = minimum possible degradation factor

λ = degradation rate parameter.

4. COMPARISONS BETWEEN SIMPLE ANALYSIS AND MEASURED RESULTS

It is found that computed degradation factors, D_τ, using $\lambda = 0.25$ and $D_{\tau \mathrm{lim}} = 0.06$, show some similarity to those obtained from the model tests.

The parameters used for the simple analysis of the load-controlled model tests are: $E_s = 22$ MPa, $\nu_s = 0.35$, $f_s = 0.13$ MPa, $D_{\tau \mathrm{lim}} = 0.06$, $\lambda = 0.25$, $m = 0.28$ and $n = 5.1$. These parameters have generally been derived from the displacement-controlled model tests (Poulos and Lee, 1988), except the parameters for permanent displacement accumulation.

Figure 6 compares the computed cyclic stability diagram for the pile subjected to 100 cycles of uniform loading, with that determined from the model tests. Considering the simple form of degradation model, the simple analysis and observed results are in reasonably good agreement.

Figure 7 demonstrates that the analysis can simulate reasonably well the "fatigue" behaviour of the model piles at various mean load levels. However, Figure 6 also shows that cyclic degradation can occur at even lower cyclic load levels than the theory predicts. Thus, adequate margins of safety should be used when assessing the possible effects of cyclic loading on grouted pile response.

5. CONCLUSIONS

The laboratory investigation of model grouted pile behaviour in calcareous sediments has revealed the following characteristics:

(i) A cyclic stability diagram provides a meaningful way of describing the response of piles subjected to various combinations of mean and cyclic load levels. For the model pile tests, two distinct zones are clearly defined: a stable zone in which cyclic loading causes no reduction in load capacity, and an unstable zone in which the pile will fail during cyclic loading within a specified number of cycles. These results are consistent with data from other field tests.

(ii) "Fatigue curves", representing the relationship between cyclic load level and number of cycles to failure, indicate that the latter can be very sensitive to cyclic load level, and that the mean load level is also a significant factor.

(iii) The general observed characteristics of the cyclic stability diagrams and "fatigue curves" of the pile can be simulated reasonably well by a simple analysis based on a simple skin friction degradation model.

The model test data clearly demonstrates that, while grouted piles in calcareous sediments may develop substantial skin friction under static loading, there is the potential for significant loss of shaft load capacity if the cyclic load level exceeds about 20% of the static shaft load capacity.

6. ACKNOWLEDGEMENT

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