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END BEARING CAPACITY OF PILES IN CARBONATE SOILS

FORCE PORTANTE A LA BASE DES PIEUX DANS LES SOLS CARBONATES

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SYNOPSIS: The results of an experimental study of the end bearing capacity of piles in layered carbonate sands are presented. Model tests are used to derive relationships for the bearing capacity in homogeneous uncemented and cemented carbonate sands. A simple procedure is then described for determining the capacity in layered systems, in which the bearing capacity is expressed as a function of the ratio of cemented layer thickness to the pile diameter. Both continuously driven displacement piles and cast-in-place piles are considered, with the latter giving a lower capacity in thin cemented layers.

INTRODUCTION

The end bearing capacity of piles in carbonate soils is of relevance in several offshore locations, including the North West Shelf of Australia, the Bass Strait, the Indian Ocean and the Middle East. Carbonate soils often include layers of cemented material, and so an extensive research programme on the end bearing capacity of piles in layered carbonate sands has been completed. This paper outlines some important results from the research and their implications for design.

The main research programme involved tests on 16mm diameter model piles in a stress-controlled testing tank 450mm in diameter and 450mm high. A supplementary test programme on piles of other sizes up to 80mm diameter was also completed. The tests involved jacking of the pile into a carbonate sand containing a layer of artificially cemented material. The variables studied included: mean stress level, ratio of horizontal to vertical stress, cemented layer thickness, cemented layer strength, pile type (closed and open end as well as a 60° conical tip) and pile installation method (designed to represent either driven or cast-in-place piles).

The results of the test programme lead to proposals for the calculation of pile end bearing capacity in layered carbonate soils. Simple procedures are used to define the bearing capacity in (a) uncemented material alone and (b) thick layers of cemented material. In this paper particular emphasis is placed on the influence of layer thickness; for thin cemented layers (typically less than 5 pile diameters thick) proposals are made for the calculation of a reduced capacity as a function of the ratio of the layer thickness to the diameter of the pile. In this paper only piles with closed ends are considered.

EXPERIMENTAL PROGRAMME

In the main series of tests model piles of diameter 16mm were continuously jacked into a cylindrical stress-controlled chamber 450mm × 450mm. The tests are shown in outline in Figure 1. The sample in the chamber was a uniform uncemented carbonate sand from Dogs Bay, Eire, deposited in a loose state. All tests were on dry sand. The properties of the Dogs Bay sand are described by Evans (1987) and Coop (1990). In the centre of the sample was a layer of artificially cemented carbonate sand. The cementing material was gypsum plaster, and consistent strength values could be achieved by use of standardised procedures. The properties of the cemented material are described by Evans (1987) and Coop and Atkinson (1992). The vertical and horizontal stresses were independently applied to the chamber by flexible membranes in the base and the cylindrical wall of the chamber.

Tests were carried out at a variety of stress levels (vertical effective stresses from 50kPa to 500kPa), $K = \sigma_h'/\sigma_v'$ values of 0.25 to 2.0, with most tests at $K = 0.5$, and a range of unconfined crushing strengths of the cemented layer from 0.65MPa to 4.0MPa. The thickness of the cemented layer was varied from half a pile diameter to 8 pile diameters.

The main series of tests was on 16mm closed-ended piles, but supplementary tests (not discussed here) on 16mm open ended piles and 60° cones were carried out, as well as tests on closed-ended piles of diameter 8mm, 32mm and 80mm (these last tests being carried out in a larger 1.5m high by 1.0m diameter chamber).

The continuously jacked tests modelled the behaviour of a driven displacement pile. A further series of tests in which the pile was

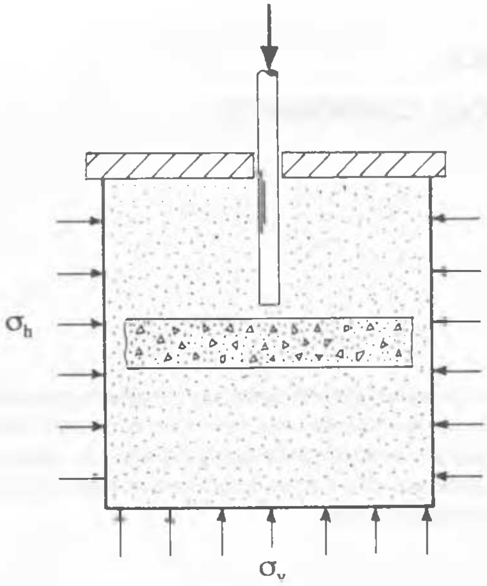

Fig. 1. Schematic design of testing chamber

initially placed at the top of the cemented layer, and the sand above that poured around the pile, modelled the behaviour of a cast-in-place pile.

EXPERIMENTAL RESULTS

For a closed-ended continuously jacked pile it was found that the end bearing capacity could be expressed in the form:

$$\frac{q_s}{p_a} = A\left(\frac{p'}{p_a}\right)^m \tag{1}$$

where q_s is the capacity in uncemented soil, p_a is atmospheric pressure, p' is the *in situ* mean effective stress, A is a constant equal to 38.0 and m is a constant equal to 0.6. Similarly it was found that in thick cemented layers (i.e. 5 diameters thick or more) an approximately constant tip resistance for continuously jacked piles was obtained, which could be expressed in the form:

$$\frac{q_r}{p_a} = B\left(\frac{\sigma_c}{p_a}\right)^n \tag{2}$$

where q_r is the capacity in cemented material, σ_c is the unconfined crushing strength of the cemented material, B is a constant equal to 32.0 and n a constant equal to 0.5. Slightly different procedures from equations (1) and (2) were suggested by Evans (1987), but the methods given here take account of more recent test results. Although based on tests on 16mm piles, they fit the behaviour of the full range of pile sizes tested from 8mm to 80mm diameter.

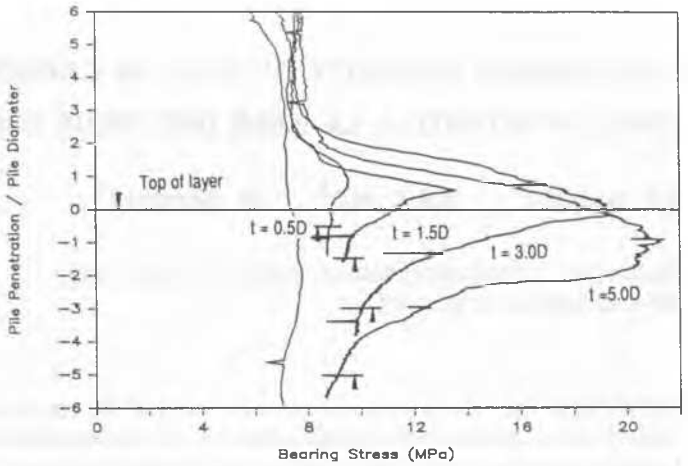

Fig. 2. Bearing capacity against depth for layer thicknesses of 0.5D to 5D

EFFECTS OF LAYER THICKNESS

The above formulae give good results for tests in homogeneous soils, but have to be modified for cases where the cemented layer is thinner than about five pile diameters. Since typical offshore piles in carbonate materials may be in the range 0.6m to 1.2m diameter, then any cemented layer less than about 3m thick must be treated as "thin". Evans (1987) and Houlsby *et al.* (1988) presented empirical data on the effects of layer thickness, but the main purpose of this paper is to *quantify* the reduction of maximum capacity due to reduced layer thickness.

The method adopted is as follows. A typical set of tests on different thicknesses of cemented layer is shown in Figure 2, which shows the penetration resistance plotted against depth for tests at $\sigma'_v = 50\,\text{kPa}$ with a cemented layer strength of $\sigma_c = 1.5\,\text{MPa}$.

For each test the peak value of the bearing capacity is given by q_m, and the factor $f = (q_m - q_s)/(q_r - q_s)$ is determined, where q_s and q_r are the values computed for the homogeneous uncemented and cemented materials respectively. The factor f, which must lie between 0.0 and 1.0, represents the fraction of the additional capacity due to the presence of the cemented layer which is mobilised by a layer of a given thickness. The value of f is zero for a very thin layer, and rises to unity for a very thick layer.

Figure 3 shows a plot of f against the ratio t/D of layer thickness to pile diameter for a total of 34 tests on three different strengths of cemented layer. Although values of f greater than unity are not theoretically possible, some are shown in the figure because the *measured* capacity of the layered system was, due to experimental variability, larger than the *computed* capacity for a very thick layer from equation (2). The apparent scatter in Figure 2 (and later figures) is not simply due to experimental variability. The points represent tests at a wide range of stress levels and

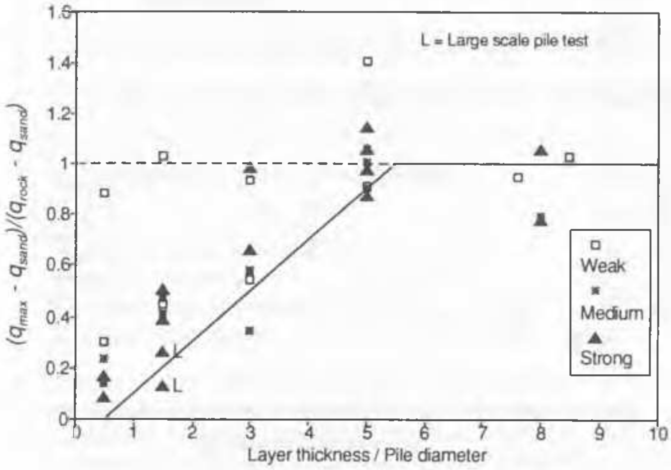

Fig. 3. Capacity factor against ratio of layer thickness to diameter

layer strengths, so that a unique curve is not expected. The lower bound to the data points is of most interest.

A reasonable lower bound to the peak capacity of the layered system is given by the expression:

$$f = (t/D - 0.5)/5.0 \qquad (3)$$

with the restriction $0.0 \leq f \leq 1.0$. This relationship is shown as the solid line in Figure 3, and may be used to estimate a safe value of the bearing capacity in layered systems.

The mechanism of failure differs for different combinations of stress level and cemented layer strength. For *strong* layers at *low* stress level the mechanism involves significant cracking of the layer, and is similar to the mechanism of punching failure of a slab. For *weak* layers and *high* stress levels, the mechanism becomes entirely ductile, with no evidence of cracking of the cemented layer. Intermediate mechanisms are observed for other combinations of strength and stress level.

In the cases where the failure is brittle, and especially for thin layers, the peak capacity is only observed for a very limited range of penetration. Of more practical application in these cases is the capacity which can be sustained for a certain range of penetration. This value will be close to the peak value in some cases, but significantly reduced in others. Figure 4 is similar to Figure 3, except that the value of f has been computed from the capacity which can be sustained for one diameter of penetration (similar plots may be prepared for other ranges of penetration). The expression for f from equation (3) is modified to:

$$f = (t/D - 1.0)/5.0 \qquad (4)$$

with $0.0 \leq f \leq 1.0$. The modification accounts for the slight reduction in capacity for this case.

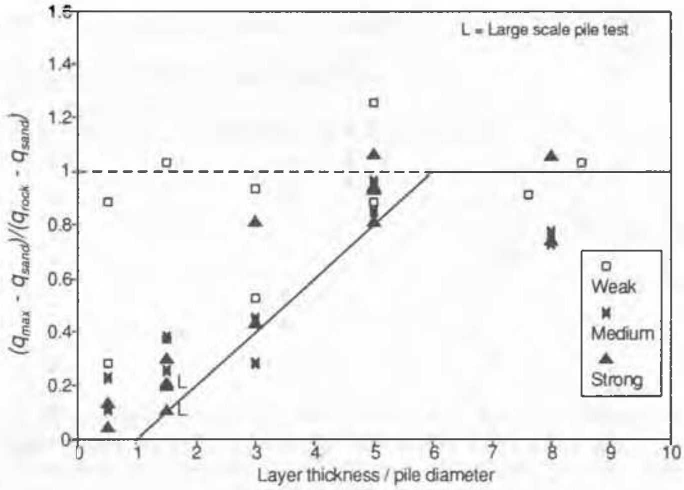

Fig. 4. Capacity factor against thickness to diameter ratio for sustained capacity over one diameter penetration

Because of the wide variety of testing conditions, the scatter in Figures 3 and 4 is not unexpected. It would be anticipated that this variability would, to a large extent, be due to the different mechanisms operating for different ratios of cemented layer strength to ambient stress level σ_c/σ_v'. This is investigated in Figure 5, which shows the variation of f with σ_c/σ_v' (on a logarithmic scale). Although there is a slightly discernable trend that, for a given layer thickness, f reduces with increasing σ_c/σ_v' ratio, the magnitude of the variation is rather small. It should be noted that at small values of σ_c/σ_v', the value of q_r is little greater than q_s, and the precise value of f in these cases has only a small influence on the calculated absolute capacity. (For typical parameter values, q_s and q_r are about equal when σ_c/σ_v' is near unity).

The above data all relate to piles which were continuously jacked into the soil. A second series of tests were carried out in which the piles were installed with the tip resting on the top of the cemented layer, and the sand above poured around the pile. After the sample had been stressed to the required level, the pile was then driven. The tests were intended to simulate cast-in-place piles, in which a bulb of highly stressed soil would not be formed continuously beneath the tip, as is the case for a driven displacement pile.

It was found that penetrations of up to about one diameter were required before the maximum capacity was reached, with this large displacement being required because of the highly compressible nature of the carbonate soil. The result is that, especially for thin cemented layers, the capacity of a cast-in-place pile is significantly less than that of the equivalent driven pile. For a very thin layer the pile has already penetrated through the layer before the peak capacity is mobilised, and so little or no benefit is derived from the layer. Figure 6 shows the equivalent to Figure 4, but for 16 tests on cast-in-place piles. The appropriate lower bound expression for the capacity factor is:

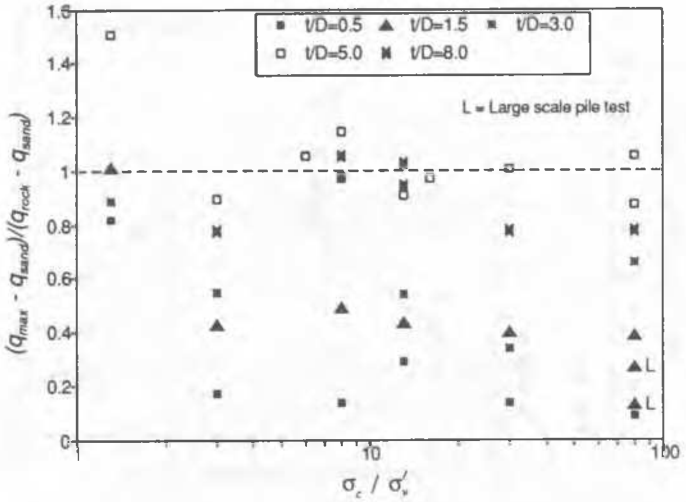

Fig. 5. Capacity factor against ratio of cemented layer strength to stress level

$$f = (t/D - 2.5)/5.0 \qquad (5)$$

with the restriction $0.0 \leq f \leq 1.0$. In order to mobilise a comparable capacity to that of a driven pile a layer about 1.5 diameters thicker is needed for a cast-in-place pile.

Piles in layered soils are often designed according to the procedure defined by Heijnen (1974), which employs weighting factors to the average and lower bound cone resistances computed within a range from 8 diameters above the pile tip to 3.75 diameters below. The cone resistance may be approximately equated to the tip capacity in a homogeneous soil. With this assumption it has been found that Heijnen's method gives a reasonable estimate of the drop-off of capacity as the pile penetrates the base of the cemented layer, but provides a less realistic fit to the pick-up of capacity near the top of the layer. It appears that the zone of soil which is considered as affecting the capacity (especially the extent of 8 diameters above the tip) is unrealistically large for carbonate soils. An improved fit can be achieved if reduced zones of influence (approximately 2 to 3 diameters) are used. This finding seems reasonable in that Heijnen's empirical procedure was based on extensive experience in The Netherlands, principally in dilatant silica sands. These materials are much stiffer than carbonate sand, which also tends to compress plastically. Cavity expansion theory would predict that the plastically deforming zone would be less extensive in the carbonate sands, so that the influence of stronger material occurs over a much shorter distance.

CONCLUSIONS

An extensive series of model tests has been used to develop new design procedures for the end bearing capacity of piles in carbonate materials. Simple calculations for the capacity in uniform uncemented or cemented carbonates are described. A method is also suggested for the calculation of the maximum capacity in a layered system, with the capacity being a function of ratio *t/D* of the thickness of a cemented layer to the pile diameter. The capacity of cast-in-place piles is lower than that of driven displacement piles, especially for thin layers of stronger material.

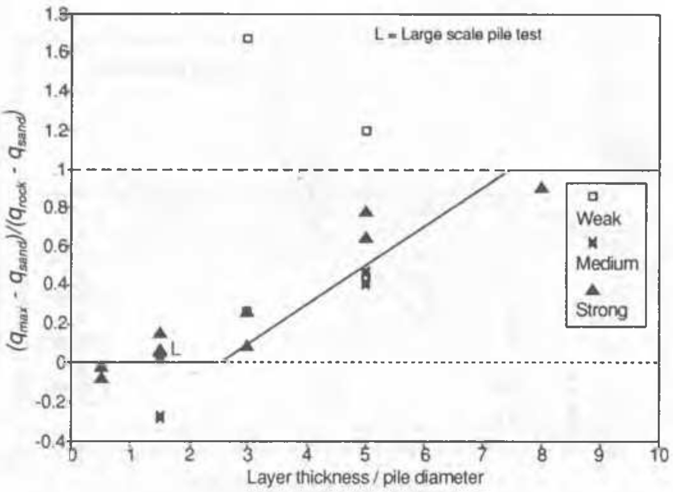

Fig. 6. Capacity factor against thickness to diameter ratio, cast-in-place piles, one diameter sustained capacity

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