The behaviour of open and closed ended piles jacked into loose sand

Le comportment des pieux ouvert à extrémités et fermées poussés dans un sable de faible densité

K.Gavin & B.M. Lehane – *Department of Civil Engineering, Trinity College, Dublin, Ireland*

ABSTRACT : This paper presents the results from a series of tests on instrumented open and closed ended piles in sand. The investigations were carried out using jacked piles of diameters between 40 and 111mm in a large chamber of carefully prepared loose sand. Factors influencing soil plug development in open ended piles are examined and comparisons are made between the behaviour of the shaft and base resistances of open and closed ended piles.

RESUME : Ce papier présent les résultats d'une série d'examens sur des pieux instrumente à bouts ouverts et fermés dans sable. Les investigations ont eté completé en utilisant les pieux poussees, entre 40mm et 111mm de diametres, dans une chambre de sable desserre et bien préparé. Les facteurs qu'influence le developpement du bouchon des sol dans les pieuz à bouts ouverts sont examines et des comparaisons sont faites entre le comportment du fût et les résistance au fond des pieuz à bouts ouverts et fermes.

1. INTRODUCTION

Research on the capacity of open-ended driven piles has, in many cases, been prompted by the needs of the offshore industry which often requires piles to be driven to large depths to develop sufficient tension capacity; these depths would not be obtainable with closed-ended piles because of their larger end bearing capacity. While many advances have recently been made in the design of closed-ended piles (e.g. Jardine & Chow 1996), assumptions made in the design of open-ended piles are less certain. The uncertainties include those associated with the estimation of the resistance to compression loading offered by the soil plug and pile annulus at the pile base and the differences between the shaft capacities of open and closed-ended piles.

Notable contributions to our understanding of the mechanisms of open-ended pile penetration in sand have been made by Hight et al (1996), O'Neill & Raines (1991) and Randolph et al (1991). This paper attempts to further expand the data base of measurements discussed by these workers by examining the behaviour of jacked model piles into loose dry sand.

2 TEST PROGRAMME

Trinity College Dublin are currently conducting a number of investigations into open-ended driven pile behaviour. The first stage of this programme, which was aimed at providing an initial insight into the mechanisms of pile penetration in sand, involved monitoring the installation (by jacking) and load testing of open and closed-ended piles with diameters (D) ranging from 40mm to 111mm. The ratio of diameter to wall thickness (D/t) of the open-ended piles was varied between 9 and 35. The objectives of this phase of the programme were to:

1. Investigate the effect of D and D/t on soil plug development
2. Compare the magnitudes and rate of mobilisation of the end resistance of closed and open-ended piles.
3. Compare the magnitudes, distribution and development of internal and external skin friction of both open and closed-ended piles

2.1 *Testing arrangement and model pile configurations*

The open-ended piles were fabricated from two steel pipes of slightly different diameters. The smaller diameter pipe was pushed into the larger pipe and machined annular end caps made the two pipes act as a single unit. These piles were also employed as closed-ended piles by fixing a rigid solid steel cap at the pile toe.

The identification system adopted for the model pile takes the form: OP/CL-D-D/t, where the designation OP or CL denotes whether the pile is open or closed-ended respectively. For example, pile OP-111-17 refers to an open-ended pile of diameter 111mm and D/t ratio of 17.

Each pile was instrumented with eight sets of strain gauges (three gauges per set). These were fixed to the outside wall of the inner pipe and inside wall of the outer pipe at four different levels corresponding to heights above the pile tip (h) of 50, 350, 900 and 1450mm. Internal and external shear stresses were inferred from the axial load distribution recorded by these gauges.

The movement of the sand plug within the pile was monitored using a lightweight disk which was attached to a rigid small diameter rod that ran up through the top end-cap. Applied loads and pile head displacement were monitored using conventional transducers.

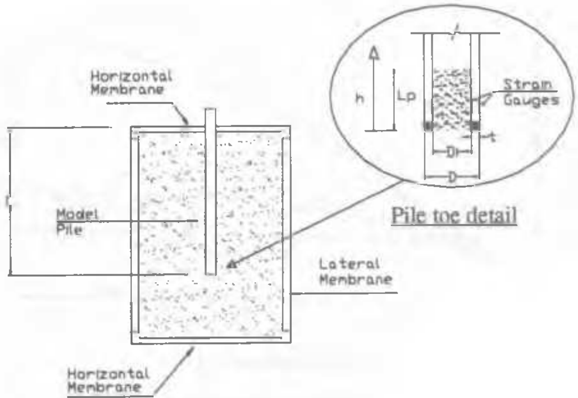

Figure 1 Pile testing chamber

A large chamber and reaction frame (Figure 1) were constructed to perform the tests. The chamber has been designed to allow independent control of the vertical and horizontal stresses applied to a large sand sample (1.6m diameter, 2.3m high). While a maximum vertical stress of 300 kPa may be applied in the chamber (simulating the stress levels around a deep pile), only those tests which involved zero applied stress are discussed in this paper.

Piles were jacked into the chamber at a penetration rate of ≈75mm/min and typically 30 strokes of the jack were used to install piles to their maximum penetration of 1.6m. Jacking rather than driving (which is known to impose additional dynamic effects; see Brucy et al. 1991) was selected for this programme of tests because of the requirement for high stability of the gauges at the anticipated low levels of applied load.

The sand employed had a mean particle size (D_{50}) of 0.2mm, a uniformity coefficient of 1.6, maximum and minimum void ratios of 0.82 and 0.53 respectively and a constant volume friction angle (ϕ'_{cv}) of 32° in direct shear. It was poured through a large purpose-built sieve located at least 600mm above the sand surface. Numerous trials using this procedure resulted in a uniform sand relative density of 28 ±3% in the chamber.

This low relative density was decided upon, firstly, to limit pre-mature plugging of the relatively small diameter open-ended piles and, secondly, to reduce boundary effects in the chamber, which can be significant in dense sands, e.g. see Parkin and Lunne (1982). Pre-mature plugging was also restricted by using relatively smooth steel (centre-line average roughness < 2μm) for the piles; the ultimate angle of interface friction (measured in direct shear) between the steel and the sand was 23° at normal stress levels between 50kPa and 150kPa.

3 PLUG DEVELOPMENT

The variation of the height of the soil plug (L_p) with pile penetration (L) during four different pile installations is shown on Figure 2. It is evident that for piles of equal diameter, the pile with the higher D/t ratio develops a higher length of soil core e.g. L_p for OP-111-17 is about 2.5 times that of OP-111-9 at L=1.6m.

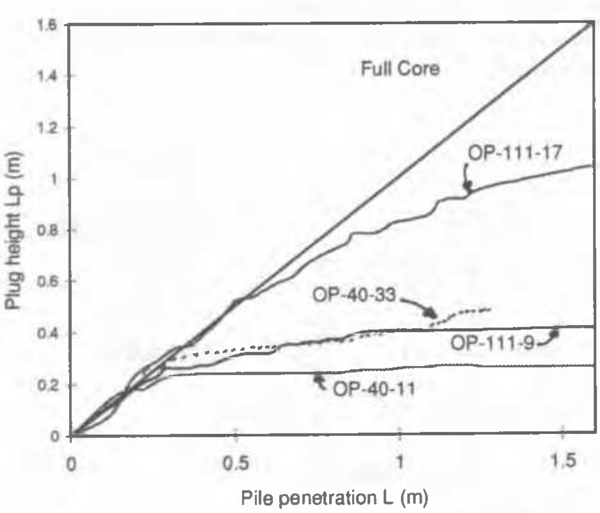

Figure 2 Plug height variation with penetration

If it can be assumed that the bearing pressures beneath the pile annuli were equal to that measured by a closed-ended pile of the same external diameter, the results obtained implied that the pressures acting at the base of soil plugs of roughly equal diameter were very similar. As shorter plug lengths were developed in piles with lower D/t ratios, it may therefore be surmised that the installation of a pile with a lower D/t ratio will result in the creation of a sand plug which has a higher vertical capacity; this may be due to increased densification of the plug at lower D/t ratios.

The process of plug development is depicted more clearly on Figure 3 which plots the variation with L/D of the incremental filling ratio (defined as the ratio of the change in core height to the change in pile penetration: ($\Delta L_p/\Delta L$). As expected, the $\Delta L_p/\Delta L$ generally reduces with L/D albeit with sporadic increases and falls. These variations are consistent with continual collapses and re-creations of sand arches as the plug length approaches its final stable length (when $\Delta L_p/\Delta L$ remains at zero). This length is shown on Figure 3 to be about 10D for piles OP-111-9 and OP-40-11 but is in excess of 15D for OP-111-17 and OP-40-33.

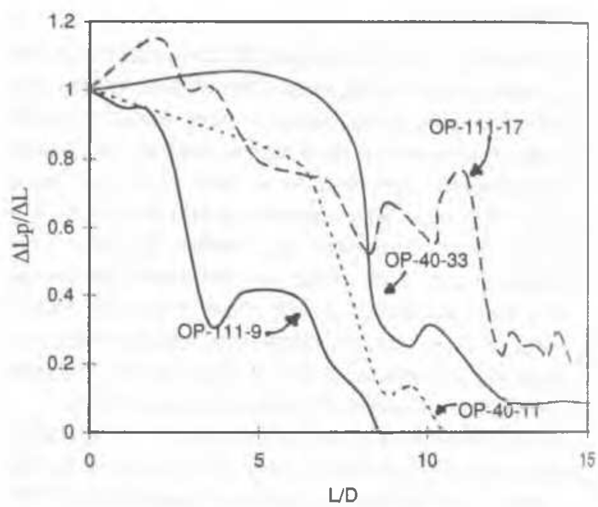

Figure 3 Incremental filling ratio with L/D

The relationship between $\Delta L_p/\Delta L$ and the resistance to penetration measured during pile installation is evident by comparison of Figure 3 with the installation resistance of 111mm diameter piles plotted on Figure 4. Both open-ended piles show the same resistance to a depth of 0.3m (≈3D) but, in keeping with the large reduction in $\Delta L_p/\Delta L$ for pile OP-111-9 at this depth, the resistance profile shows a significant change in curvature and the pile shortly afterwards attains the resistance generated by an equivalent closed-ended pile.

4 PILE BASE RESISTANCE

The base capacity of an open-ended pile arises from a combination of the resistance offered by the pile's steel annulus and its plug. For the purposes of comparison in the following, the pile end bearing stress (q_b) for the open-ended condition is taken to be an average value at the base equal to the applied pile head load minus the external skin friction divided by the total base area.

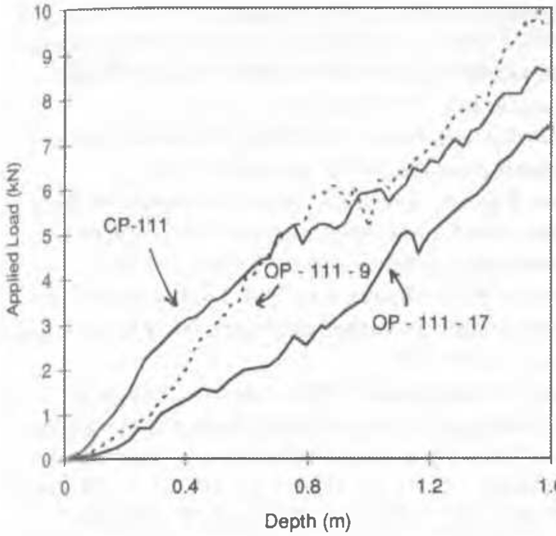

Figure 4 Applied load variation with penetration

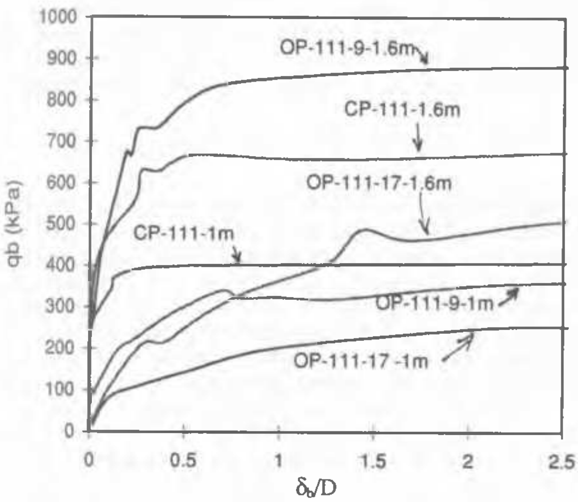

Figure 5 Average base pressure variation with δ_b/D

Table 1 Base capacities and average stiffnesses

Pile	Length (m)	E' (MPa)	q_{ult} (kPa)
OP-111-17	1.0	22	280
OP-111-17	1.6	48	600
OP-111-9	1.0	35	370
OP-111-9	1.6	105	900
CL-111	1.0	56	420
CL-111	1.6	90	700

Variations of q_b with δ_b/D (where δ_b is the settlement of the pile base) measured in static load tests on open and closed-ended 111mm diameter piles are shown on Figure 5. If linear elasticity is assumed, these curves correspond with the equivalent Young's moduli (E') of the sand at δ_b/D = 0.5% provided in Table 1. Ultimate base capacities (q_{ult}) measured in the tests on these piles are also listed in Table 1.

The base stiffness of the open ended piles at L=1.0m are only 30 to 60% of that of the closed-ended pile CL-111. This is despite the fact that OP-111-9 had become fully plugged prior to the load test. The q_{ult} value for OP-111-9 at L = 1m is, however, not far short of that of the closed-ended pile.

The E' values inferred for load tests performed at L=1.6m are higher than those at L=1m. Increases in E' and q_{ult} for OP-111-17 and CL-111 are approximately in proportion to the increase in pile penetration but the increase in E' for OP-111-9 is almost threefold, becoming even greater than the E' value inferred for the closed-ended pile.

It may be concluded that the q_{ult} value of an open-ended pile that has plugged is similar to that of a closed-ended pile but that the pile requires further penetration in the fully plugged mode to attain a base stiffness comparable to that of a closed-ended pile. The considerably lower base stiffness of a pile that has not plugged clearly has important design implications.

5 SHEAR STRESSES

The strain gauging allowed separate estimation of the internal and external shear stresses (τ_{rzo} and τ_{rzi}). A typical example of the variations in both sets of τ_{rz} values is shown on Figure 6 which plots the data obtained during installation of OP-111-17. These τ_{rz} values and those discussed subsequently were calculated assuming a linear variation in load between each level of strain gauges (i.e. implying τ_{rz} is constant) and are taken to be representative of those shear stresses acting midway between the gauge locations.

Notable trends shown by the shear stress records are listed below.

1. τ_{rzo} during open-ended pile penetrations was typically 20% less than that measured when the piles were penetrating in the fully plugged/closed-ended mode. The deviation between the shear stresses recorded in both modes decreased as $\Delta L_p/\Delta L$ reduced to values below 0.5.

2. τ_{rzo} in any fixed soil horizon reduced as the pile tip penetrated to deeper levels, i.e. τ_{rzo} reduces as the distance from the pile tip

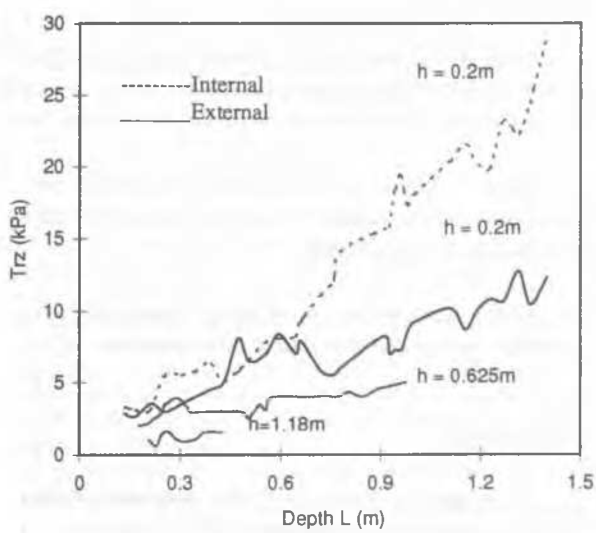

Figure 6 Shear stress during installation of OP-111-17

(h) increases. This trend, which is clearly evident on Figure 6, is now an accepted feature of driven pile behaviour in sands e.g. see Lehane & Jardine (1994).

3. In keeping with observations summarised by Jardine & Chow (1996), the reduction in τ_{rzo} with h was more pronounced when piles were un-plugged.

4. Internal shear stresses (τ_{rzi}) showed far more dramatic reductions with distance from the pile tip than τ_{rzo}. For example, no shear stress was transferred to the pile wall at h >0.35m in OP-111-17, despite the fact that $\Delta L_p/\Delta L$ was greater than zero.

5. Internal shear stresses close to the pile tips were appreciably larger than the corresponding external shear stresses e.g. τ_{rzi} calculated at h=0.2m is seen on Figure 6 to be least double τ_{rzo} at h=0.2m. Given the strong non-linear reduction in τ_{rzi} with h suggested by (4), it is likely that maximum τ_{rzi} values are considerably larger than those plotted on Figure 6.

6. The lower base stiffness of open-ended piles tested at a relatively high $\Delta L_p/\Delta L$ installation value (e.g. see Table 1) is primarily due to the observed larger displacements required to develop full internal frictions in these piles.

7. Maximum τ_{rzo} values recorded in compression load tests were typically 25% larger than those recorded in tension tests and required lower pile head movements for their full development. τ_{rzi} maxima (at h=0.2m) in tension were only about a half of equivalent values measured in compression.

6 CONCLUSIONS

Within the range of parameters examined in the test series, it may be concluded that for jacked piles in loose sand:

1. The rate of soil intrusion into an open-ended pile depends primarily on the pile diameter (D) but is also partly controlled by ratio of D to the pile wall thickness (t).

2. Open-ended piles can achieve base stiffnesses and capacities comparable to closed-ended piles, providing pile penetration in the fully plugged mode has occurred for a number of pile diameters.

3. Internal skin frictions are significantly higher than external skin frictions even before plugging occurs, and reduce at a faster rate with the distance from the pile tip (h) than external frictions.

4. External frictions for un-plugged open-ended piles in compression are only marginally less than equivalent values of closed-ended/fully plugged piles.

5. Internal shear stresses of un-plugged open-ended piles in compression can be more than double those in tension.

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