10 FIELD MEASUREMENTS OF PIPE PILE BASE RESISTANCE IN MEDIUM DENSE SAND

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SUMMARY: This paper presents the results from installation and load tests on an instrumented, open-ended model pile that was jacked into a loose to medium dense sand deposit. The model pile had an external diameter of 168 mm; a wall thickness of 9.0 mm and its twin-wall design allowed the continuous measurement of the internal and external shaft loads; the effective radial normal stress and the internal sand column length (plug length). The tests were performed to study the factors that affect plug formation and the effects of plugging on the shaft and base resistances mobilised during installation and load testing. The pile installation resistance decreased when the pile tip moved through a weaker layer and increased with a reduction in the incremental filling ratio (IFR). The base resistance values predicted using the University of Western Australia design method, which uses the IFR values measured during installation as inputs, were in good agreement with the measured base resistance values. This suggests that the pile installation resistance and axial load capacity can be predicted with confidence if the IFR value could be accurately predicted in advance of installing the pile.
Keywords: base resistance, field measurements, incremental filling ratio, model piles, pipe piles, sand, plugging.

INTRODUCTION

The axial load bearing resistance of a pile foundation is derived from the end bearing stresses (q_b), which are developed at the pile tip, and the shaft friction (q_s) that is developed between the pile shaft and the surrounding ground. For an open-ended pile, where a soil plug forms inside the pile cavity, the unit base resistance (q_b) is a combination of the stress developed around the pile annulus (q_{ann}) and the stress developed by the soil plug (q_{plug}):

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$$q_b = \frac{q_{\text{plug}} R_i^{\,2} + q_{ann} 2Rt}{R^2} \quad (1)$$

where R_i is the internal radius; R is the external radius and t is the pile wall thickness.

Recent model and full-scale, instrumented pile tests[1, 2] have shown that the degree of soil plugging during installation strongly affects the resistance mobilised during static load tests. Model pile tests in which a 111-mm diameter pile was jacked into a loose sand[3] have show that the annular resistance (q_{ann}) developed at the base of the pipe piles during installation is approximately equal to the Cone Penetration test (CPT) end resistance (q_c) value. Moreover, the plug resistance (q_{plug}) was a function of both the CPT q_c and incremental filling ratio (IFR: defined as the rate of change of the plug length with respect to the pile penetration). Static load tests were also performed on these model piles, which were loaded using a maintained-load procedure until the pile head displacement had reached 10% of the pile diameter (D). All the piles remained fully plugged during the static load tests, regardless of the IFR values measured prior to the load tests. The base resistance tended to develop relatively quickly during the static load tests on the jacked piles due to the presence of residual stresses at the base of the small diameter piles. The q_{plug}/q_c value generally ranged between 0.1 and 0.2 when the IFR value measured during the final installation jacking stroke leading up to the static load test was nearly 100% (pile fully coring). This is consistent with estimates of the base resistance mobilised for fully coring pipe-piles and bored piles[4]. As the pile begins to plug during installation (i.e. reduction in IFR value), the q_{plug}/q_c value measured during the static load tests increased and approached unity in cases where the pile was load tested after been driven a distance of 6 to 7 D in fully plugged mode (IFR = 0%).

Recognising that most field piles are driven into dense sand deposits, Gavin et al.[5] reported a number of load tests performed on model piles (ranging between 75 and 114 mm in diameter) that had been jacked or driven into dense sand. All the model piles remained plugged during static load testing although the installation technique (driving or jacking) had a major bearing on the degree of plugging during installation. A key finding was that the q_{plug}/q_c values mobilised by piles with a given installation IFR value were comparable with those measured during similar experiments in loose sand, with the q_{plug}/q_c values increasing linearly as IFR reduced.

Gavin et al.[5] proposed the following expression to estimate the plug resistance developed at relatively large pile-head displacements (about one pile diameter):

$$q_{plug} = (0.8 - 0.7\ FFR)\ q_c \quad (2)$$

where FFR is the IFR value measured during the final installation stroke leading up to the load test.

Gavin and Lehane[6] and Xu et al.[7] compiled databases of full-scale static load tests on pipe piles in sand deposits to investigate whether such a simple expression could be reliably applied to full-scale piles. Whilst a number of researchers[7–10] have shown convincing evidence that the base resistance of pipe piles reduces as the pile diameter increases, both Gavin and Lehane[6] and Xu et al.[7] suggested that this trend was caused by the tendency for larger diameter piles to have higher IFR values.

The University of Western Australia (UWA–05) design method[11], which estimates the base pressure mobilised at a pile head displacement of 10% of the pile diameter, considers the effect of plugging in its formulation. The method estimates the annular and plug resistances separately, namely:

$$q_{ann0.1} = 0.6\ q_c \tag{3a}$$

$$q_{plug0.1} = q_c\ (0.6 - 0.45\ FFR) \tag{3b}$$

where FFR (final filling ratio) is the IFR value measured over the final three diameters of penetration. It is recommended that the q_c value should be averaged over ±1.5D in relatively uniform ground conditions. However, the 'Dutch' method[12, 13] should be used for variable ground conditions.

Numerical analyses[4] and model tests[3] have shown that pipe piles with plug lengths greater than five pile diameters will plug during static loading regardless of the plugging response during installation. Although the ultimate base resistance may be large, significant pile head displacements of between 6 and 7 D may be required to mobilise this resistance. Hence, the base resistance mobilised during a static load test to a typical pile head displacement of about 10% D is controlled by the stiffness response of the sand directly below the pile plug, which in turn is related to the degree of plugging experienced during pile installation[14,15]. The effect of IFR during installation on the plug stiffness, and hence the rate of mobilisation of the end-bearing resistance on ostensibly plugged piles, is accounted for in the UWA–05 design method.

Although the importance of IFR has been confirmed by field and laboratory experiments[1,3,7], many of the recent design approaches developed to estimate the end bearing resistance of piles in sand deposits do not consider IFR in their formulation[7]. Although it has been noted that the majority of the model and full-scale pipe piles appear to plug during static load testing, the mechanisms controlling plugging during installation, which subsequently control the stiffness response of the pile base resistance during static loading, are poorly understood. The UWA–05 design method includes an empirical formulation (developed on the basis of the limited database information[11]), to estimate the final filling ratio (FFR) as a function of the internal pile diameter (D_i):

$$FFR = min\ [1, (D_i(m) / 1.5)^{0.2}] \tag{4}$$

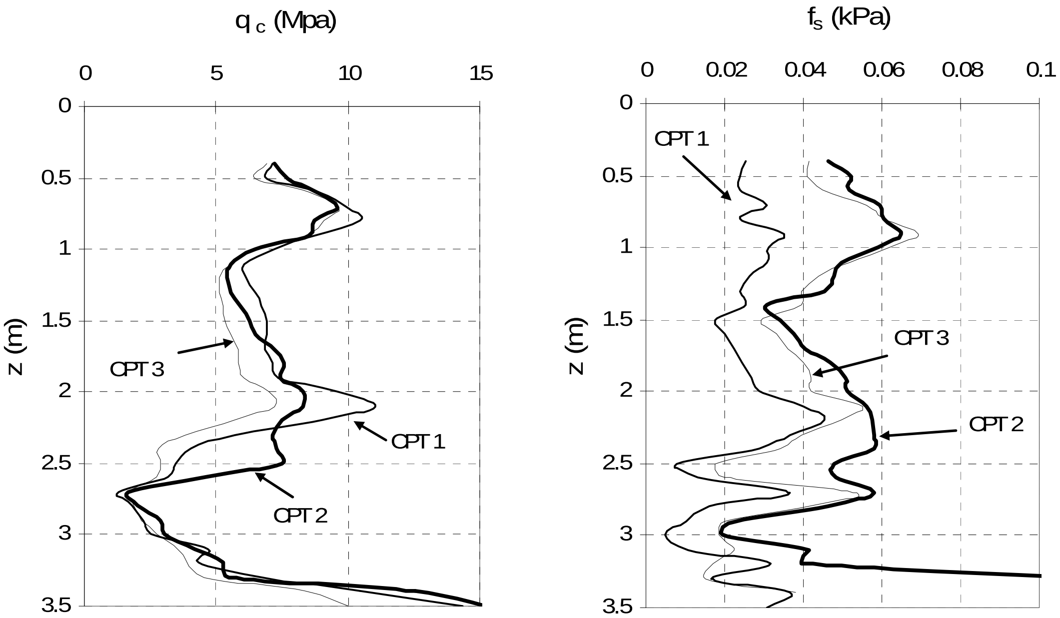
Based on model pile tests performed in a calibration chamber, Paik and Salgado[16] proposed a linear correlation between IFR and the plug length ratio (PLR: defined as plug length/pile penetration) for relatively homogenous ground conditions. Lehane and Gavin[17] presented field evidence of partial coring behaviour for driven piles and suggested that rapid changes in IFR, which occur for non-uniform ground conditions typically encountered in the field, caused great uncertainty when using simple empirical models that link IFR to parameters such as PLR and D_i.

Given the lack of field measurements on pipe pile response, a field test programme was performed using an instrumented, open-ended pile in a loose to medium-dense sand deposit. This paper studies, in particular, the effect of pile plug development on the mobilisation of the base resistance during the installation of the pile.

DESCRIPTION OF EXPERIMENTS

Site conditions

The pile tests were carried out at Donabate, North County Dublin, Ireland. The ground profile at the test site comprised a sand layer to 4.2 m below ground level (bgl), overlying a soft clay layer that became stiff at 5.1 mbgl. The medium dense sand layer (dense state below 3.5 mbgl) included a peaty layer between 2.6 and 2.8 mbgl. The equilibrium groundwater table was located at the base of the sand layer. Figure 1 shows the end resistance (q_c) and sleeve friction (f_s) profiles from three CPT tests in the immediate vicinity of the test pile.



(a) End resistance

(b) Sleeve friction.

Fig. 1: *Cone penetration testing.*

The CPT profiles indicate highly variable q_c values from ground level to about 1.0 mbgl and for this reason the test pile was installed in a 1.0-m deep starter hole. The q_c resistance in the sand layer gradually increased with depth from about 5 MPa (1.0 mbgl) to 8 MPa (depth at which peat layer starts to affect the q_c resistance, i.e. between 2.1 and 2.6 mbgl). The q_c value reduced to about 1.2 MPa in the peat layer but rapidly increased to between 12 and 15 MPa in the underlying dense sand layer. The sleeve friction values in Fig. 1(b) are more variable than the q_c values although the profiles at the three CPT test locations were generally consistent.

Experimental setup

The open-ended model pile used in this study was developed at University College Dublin using the twin-walled technique[3,18–20] that allows separate measurements of the shaft and base resistances. The pile is 2.0 m in length and has an external diameter of 168 mm and a wall thickness of 9.0 mm (Fig. 2).

Fig. 2: *Open-ended model pile.*

The total earth pressure and the pore pressure responses are measured by an array of sensors located at three different levels along the length of the pile. The total normal stress is directly measured using sensors recessed in the outer wall surface of the pile. Miniature pressure transducers (Kyowa PS-5KA), which have a diameter of 6.0 mm and a full-scale range of 500 kPa, were mounted behind porous ceramic discs that were located flush with the outer wall surface. A small gap between the pressure transducers and the outer ceramic discs ensured that only hydraulic pressure acted on the transducer face. The total normal stress and pore pressure sensors were mounted diametrically apart at h/D spacings of 1.5, 5.5 and 10 (where h/D is the distance from the pile base normalized by the external pile diameter).

Electrical-resistance strain gages, which were glued to the inner and outer wall surfaces at different levels along the length of the pile, allowed the load distribution along the outer wall surface as well as the annulus and internal plug loads to be independently measured throughout testing.

PILE INSTALLATION

The test pile was installed from the base of a 1.0-m deep trench to a final depth of 2.9 mbgl using a 20-tonne capacity CPT truck. The pile was jacked at a rate of 20 mm/s and fully unloaded following each 100 mm penetration in order to monitor the development of the pile plug. The applied load at the pile head was measured using a load cell. Two displacement transducers (attached to an independent reference beam) measured the vertical displacement of the pile head during a series of static and cyclic load tests performed after the pile had been installed to the final installation depth.

Pile plugging

The development of the soil core during the installation of an open-ended pile is dependant on a number of factors including, for example: pile diameter; wall thickness; wall surface roughness; soil layering and the mode of installation. The profile of IFR values measured during installation (Fig. 3) indicated that the test pile was fully coring (IFR = 1.0) to a depth of 1.7 mbgl (i.e. 4D penetration). Further penetration caused a plug to form with full plugging (IFR = 0) occurring at a depth of about 2.2 mbgl (i.e. 6.5D penetration). In general, the pile remained in a nearly fully plugged condition to the final depth of 2.9 mbgl although partial coring was evident (IFR = 20%) as the pile tip reached the underlying peaty layer.

Installation resistance

Figure 4 shows the total resistance including its components of base resistance (Q_b) and external shaft resistance (Q_s) mobilised during pile installation. The total resistance increased gradually with depth to about 135 kN at 2.2 mbgl after which it decreased sharply, mirroring the CPT profiles (Fig. 1). Between 60% and 80% of the installation resistance was mobilised at the pile base with the peak value occurring at about 2.1 mbgl. The rate of increase of the total resistance accelerated slightly with the onset of plugging at a depth of about 1.7 mbgl due primarily to an increase in the pile base resistance.

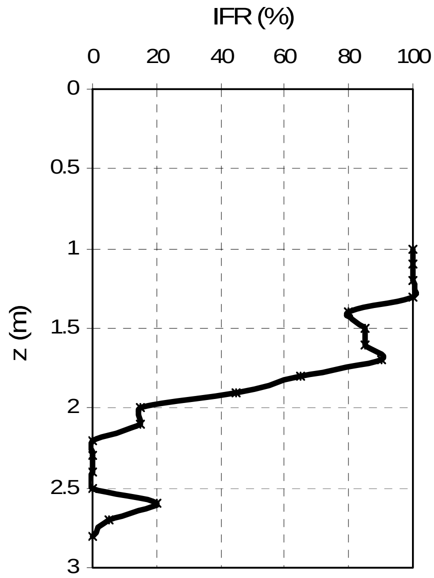
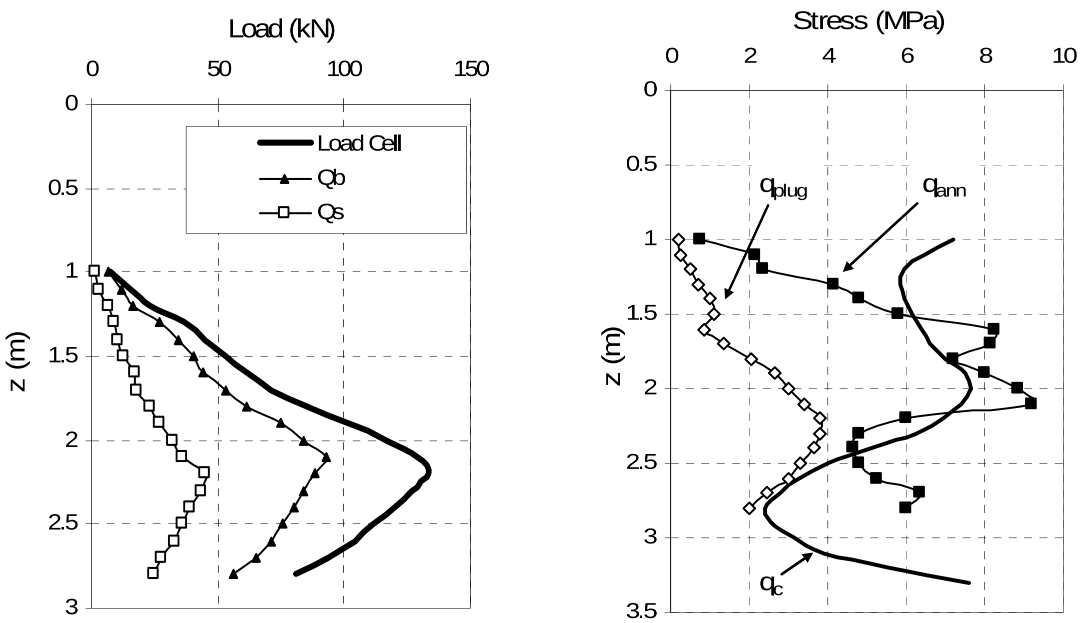


Fig. 3: *IFR values measured during installation of test pile.*



(a) Total pile resistance.

(b) Unit base resistance.

Fig 4: *Pile resistance mobilised during installation.*

The effect of plug development on the base resistance is best understood by considering the mobilisation of the unit annular and plug resistance values during installation (Fig. 4(b)). At depths greater than 1.4 mbgl (commencement of plugging), the plug resistance was found to increase strongly whereas the annular resistance was similar in value to the q_c response. The plug resistance approached the measured q_c value below 2.2 mbgl since the pile was jacked in fully plugged mode (IFR = 0). However, the contribution of the plug resistance to the total resistance was somewhat limited by the effect of the underlying peaty layer. The internal shaft resistance (q_{s_in})

mobilised at distances of 0.5, 1.5 and 2.75 pile diameters (D) above the pile tip during installation are shown in Fig. 5.

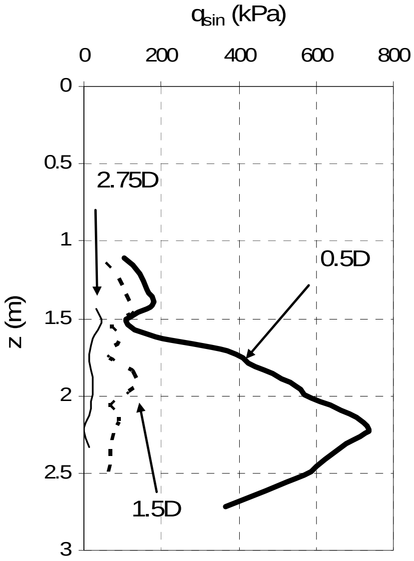


Fig. 5: *Internal shaft resistance mobilised in the vicinity of the pile tip.*

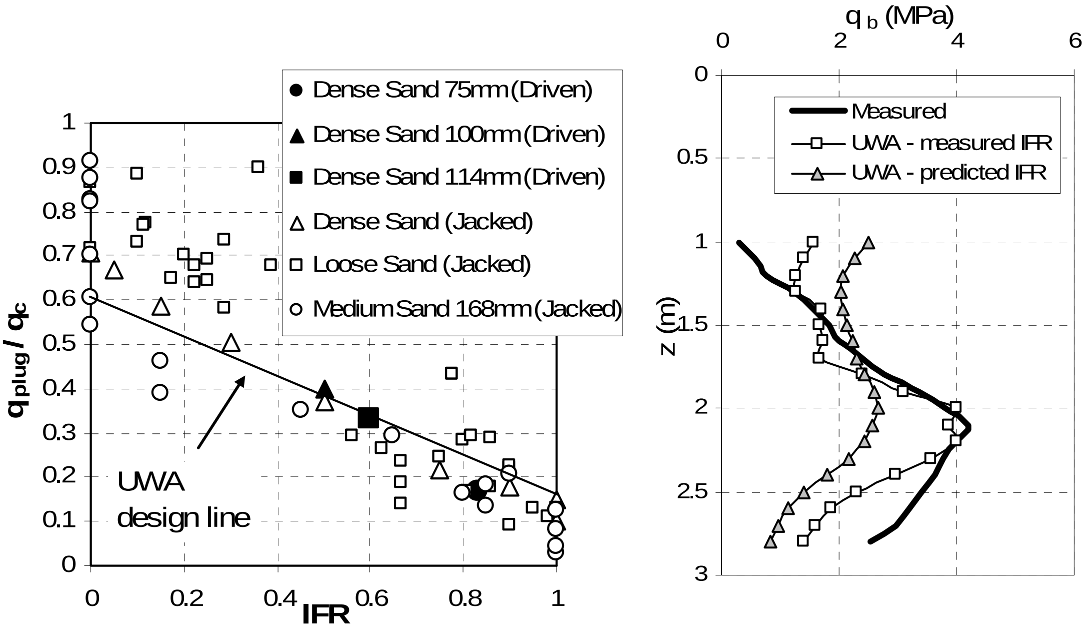
The internal shear stresses in the pile plug were confined within the lowermost three diameters of the plug throughout installation. The stress distribution varied considerably along this section of the plug ('wedged plug') once plugging had commenced. The internal shear stresses remote from the pile tip remained broadly similar as the pile moved from a partly plugged to a fully plugged state between 1.4 and 2.2 mbgl. In contrast, the internal shear stresses in the vicinity of the pile tip increased significantly over the same penetration depth, reflecting the tendency for the plug resistance to become concentrated in the lowermost one diameter of the pile plug.

Figure 6 shows the normalized plug resistance (q_{plug}/q_c) values mobilised during installation plotted against IFR. Also included are the data reported for the installation of a 111-mm diameter pile that had been jacked into loose sand by Gavin[2] and jacked into dense sand by Gavin and Lehane[6] as well as static load test results for driven piles in dense sand[6].

The following are concluded from inspection of Fig. 6:

- The response of piles installed in loose, medium-dense and dense sands are comparable when the effects of the level of densification and plugging are accounted for using measured q_c and IFR values, respectively.
- The installation data (open symbols, Fig. 6(a)) indicates in the case of IFR $\geq$ 0.5, many of the measured q_{plug} values plot below the UWA–05 design line. This may be explained, in part, by the fact that these high IFR values were generally recorded during the early stages of pile installation so that the plug lengths would have been relatively small (some pile plugs were less than 5D in length).
- In the case of IFR < 0.5, most of the measured q_{plug} values plot above the UWA–05 design line. This can be explained by the fact that the jacking stroke length used in the pile installations were typically between 50% and 100% of the pile diameter. Such an under-prediction would be expected since the UWA–05 design method (Eq. 3b) estimates the plug resistance value at 10% of the pile diameter.

- Good estimates of the plug resistance values mobilised by driven piles at 10% of the pile diameter (closed symbols, Fig. 6(a)) are obtained using the UWA–05 design method. Note that the IFR values measured during installation were used in Fig. 6(a), even though the driven piles remained fully plugged during the static load tests.



(a) Normalised plug resistance. (b) Base resistance.

Fig. 6: *Comparison of measured pile resistances with UWA–05 design method*[11].

The unit base resistance (q_b) measured during the installation of the test pile is compared with that predicted by the UWA–05 design method (Fig. 6(b)) on the basis of the measured IFR profiles (Fig. 3) and an IFR profile obtained using Eq. 4. In general, the UWA–05 design method was found to provide a good prediction of the mobilised base resistance values throughout installation when the measured IFR values are used in the computations. The method tends to over predict the base resistance values over the first 0.3-m penetration (plug lengths < $3D_i$) and to under predict the base resistance over the final 0.6-m penetration (fully plugged mode). The latter can be explained by the accelerated development of the residual base stresses after plugging[15], which results in a more rapid mobilisation of the base resistance available during static load tests.

In contrast, a constant IFR value (63% in the case of the test pile) is obtained when the IFR profile is predicted using Eq. 4. The plug resistance is singly dependent on the q_c value so that the UWA–05 design method tends to significantly over predict the base resistance mobilised during the initial stages of installation and under-predict the base resistance after the pile plugs.

Although the UWA–05 design method was primarily developed for full-scale driven piles with long soil plugs, the essential mechanics controlling the development of the base resistance of pipe piles also appears to be captured by the design approach.

SUMMARY AND CONCLUSIONS

Field measurements of the plug and base resistance values mobilised during the installation of an instrumented open-ended model pile in a medium-dense to dense sand deposit have been presented.

It was found that the jacking load required to install the pile was a function of the CPT q_c and increment filling ratio (IFR) values. Between 60 and 80% of the installation load was resisted at the pile tip, the majority of which was taken by the pile plug. The unit annular resistance value was approximately equal to that of the q_c response throughout installation. The normalised unit plug resistance (q_{plug}/q_c) increased as IFR decreased with q_{plug}/q_c continuing to increase as the pile penetrated in fully plugged mode (IFR = 0). The majority of the resistance mobilised in the plug occurs in the "wedge" section located within two diameters of the pile tip.

The UWA–05 design method provided good predictions of the mobilised base resistance when the IFR values that had been measured during pile installation were used in the computations.

At present, designers have no accurate method of predicting the IFR value of pipe piles in advance of installation. The recommendation by Lehane and Gavin[17] for routine field measurements of IFR values during the installation of open-ended piles is reiterated and an important short-term aim should be the development of a simple but reliable IRF prediction method.

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