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A comparison of jacked, driven and bored piles in sand

Comparaison des pieux fonçés, battus et forés dans les sables

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ABSTRACT
Pile jacking technology allows displacement piles to be installed without noise and vibration. The 'press-in' method of pile jacking uses previously-installed piles for reaction, so the piles must be installed at close centres. Axial load tests have been conducted to investigate whether existing design guidance based on driven and bored pile behaviour can be applied to closely-spaced jacked piles. The observed axial response was notably stiff, and failure was reached at a load equal to the installation force. This high stiffness is attributed to pre-loading of the pile base during installation and the presence of residual base load. Load transfer back-analysis was used to establish simple parameters for the modelling of single pile stiffness. These parameters predicted the pile group response well using elastic superposition to account for interaction. This high stiffness could lead to more efficient design if jacked piles are used.

RÉSUMÉ
La mise en œuvre des pieux par fonçage permet d'installer des pieux sans immissions sonores et sans vibrations. Le fonçage des pieux utilise la réaction des pieux installés, de sorte que l'entre-axe des pieux doit être rapproché. Des essais de chargement axiaux sur des pieux et sur des groupes de pieux foncés ont étés effectués afin de déterminer si les codes de dimensionnement pour les pieux battus et forés peuvent être appliqués aux pieux foncés proches les uns des autres. Une grande rigidité des pieux sous charge axiale a été mesurée. Cette rigidité est attribuée au préchargement de la base du pieu lors de son installation et à la présence de charges résiduelles à la base du pieu. Des analyses du transfert des charges ont étés effectuées pour identifier des paramètres pour la prédiction de la rigidité des pieux isolés. Ces paramètres ont permis une bonne évaluation du comportement du groupe de pieux, moyennant modifications par superposition élastique pour tenir compte des interactions entre les pieux.

1 INTRODUCTION

The strength and stiffness of a pile foundation is influenced by the installation method. Modern techniques of pile construction have led to improved foundation performance. To benefit from this improved performance, design methods must be modified to account for the influence of construction method on strength and stiffness. If a foundation can be constructed from a smaller number of stiffer piles, economies of cost, construction time and environmental impact through reduced material use can result.

This paper describes an investigation into the response of jacked displacement piles in sand. One pile jacking technique is the 'press-in' method, in which reaction force for the jacking machine is obtained from previously installed piles. The 'press-in' piling machine shown in Figure 1 installs tubular piles of diameter 1000-1200 mm with a jacking force of up to 3 MN.

Pile jacking technology allows pre-formed displacement piles to be installed without the environmental impact of dynamic methods. The use of static jacking force applied using hydraulic rams avoids the noise and ground vibration associated with conventional dynamic methods. Previous research has demonstrated that pile jacking reduces ground-borne vibrations by an order of magnitude compared to traditional percussive and vibro-hammer installation techniques (Rockhill et al 2003). Pile jacking machines with capacities of up to 4 MN are currently in operation (White et al 2002, Lehane et al 2003).

Since 'press-in' piling machines 'walk' along the pile wall as construction advances, the piles must be installed at a nominal centre-to-centre spacing of one diameter. This geometry conflicts with conventional design guidance, which advises a minimum pile spacing of 2 or 3 diameters (BS8004, 1986; GEO, 1996). This advice aims to eliminate interaction between the piles, to avoid reduced pile stiffness or strength. Existing design methods may be inadequate for predicting the axial response of piled foundations installed using pile jacking technology for two reasons:

1. The axial stiffness of the pile may differ from conventional piles due to the jacked installation.
2. Current design methods for pile groups have not been tested against piles installed at spacing ratios as low as unity.

Field load tests have been conducted to examine these two uncertainties. A series of maintained load tests (MLT) on jacked-in, open-ended tubular piles are reported. These piles were either alone, in a short wall, or in a group of up to 12 piles. Back-analysis of the load-settlement response is carried out using a load transfer approach.

Figure 1. A 'press-in' piling machine for installing large tubular piles

2 METHODOLOGY

2.1 *Ground conditions*

This series of pile load tests was conducted during summer 2003 at the Takasu test site located in Kochi, Japan. The ground conditions comprise made ground overlying layers of silt, silty sand and sand (Fig. 2). Prior to installation of the test piles the made ground was excavated and replaced by sand.

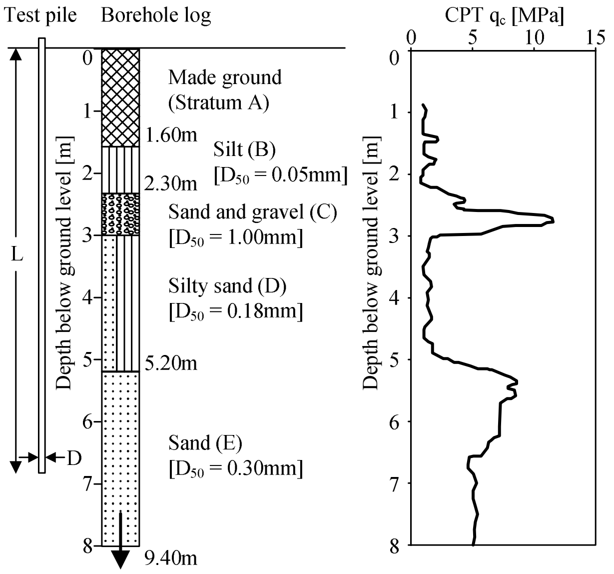

Figure 2. Ground conditions at test site

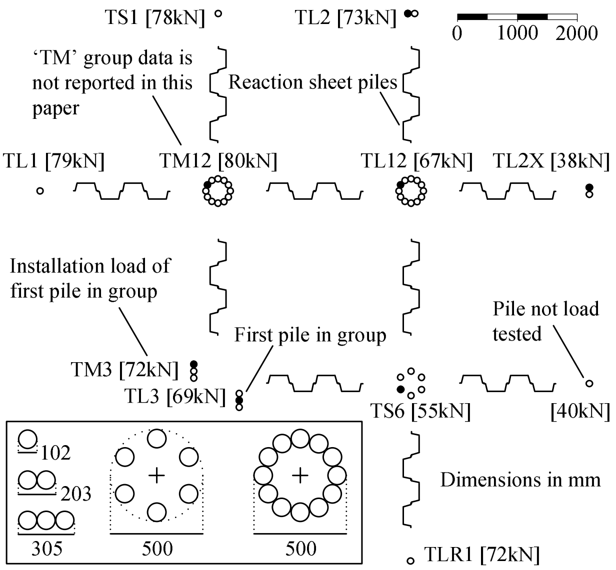

Figure 3. Arrangement of test piles

2.2 *Test piles*

The test piles were uninstrumented open-ended steel tubes with an external diameter, D, of 4 inches (101.6 mm) and a wall thickness of 5.7 mm. Two lengths, L, of test pile were used, with embedded depths of 5.85 and 6.85 m. A total of 43 piles were tested, either alone, in short walls of 2 or 3 piles, or in circular groups of 6 or 12 (Fig. 3). A Giken AT150 'press-in' piler was used to install the piles in jack strokes of 700 mm. Reaction force was provided by sheet piles located at a minimum distance of 600 mm (~6D) from the test piles. The maximum jacking resistance was encountered during the final stroke, and was recorded by a load cell between the pile head and the piler.

2.3 *Load test procedure*

A hydraulic jack was used to apply force through a load cell to the head of the single piles, or to a steel cap mounted on the pile groups. Pile head settlement, w, was monitored relative to independent reference beams. Six equal load increments were applied up to 75% of the installation force of the test pile (or n times the installation force of the first pile for groups of n piles). A further 4-6 smaller load steps took the pile to plunging failure. An unload-reload loop was conducted after a settlement of D/10 (10 mm). Each load increment was maintained until the pile head settlement rate was less than 0.02 mm/minute.

3 BACK-ANALYSIS: LOAD TRANSFER METHOD

Back-analysis of the observed load-settlement response has been conducted using the RATZ load-transfer program (Randolph 2003). This program combines parabolic models for the local shaft (τ_s-z) and base (q_b-z) resistance response with elastic compression of the pile to calculate the resulting pile head load–settlement response. The parabolic τ_s-z model requires the initial operative soil stiffness, G_{oper}, to be estimated, in addition to the limiting local shaft resistance, τ_{sf}. The initial slope of the parabolic τ_s-z response is G/2D following the elastic solution of Randolph & Wroth (1978). The parabolic base response is defined by the limiting base resistance, q_{bf}, and the settlement required to mobilise this resistance, w_{bf}. The initial slope of the parabolic q_b-z response is $2q_{bf}/w_{bf}$.

The pile groups were modelled using an interaction factor approach. The 'elastic' response of a pile element, defined by the initial stiffness of the τ_s-z and q_b-z parabolae, was softened by a settlement ratio, denoted R_s for the shaft and R_b for the base. The 'plastic' component of settlement, represented by the parabolic deviation from the initial stiffness, remained unchanged. R_s and R_b were calculated as the proportional increase in settlement of a pile element due to the additional settlement contributions created by the neighbouring piles. It was assumed that the piles within each group carried equal load. Following Randolph & Wroth (1979), the settlement trough around the shaft was estimated from the Randolph & Wroth (1978) elastic solution, whilst the settlement around the base was estimated from an approximation of the elastic rigid punch solution.

4 RESULTS

4.1 *Pile installation*

A rigid plug formed within each pile during jacking. Plug lengths in the range 0.8-2.5 m were recorded after installation. All piles failed in a plugged manner during load testing. The jacking force at the end of the final installation stroke, $Q_{install}$, is shown in Table 1 and on Figure 2.

Table 1. Summary of test programme

Description [-]	ID. [-]	n [-]	L [m]	$Q_{install}$ [kN]	Q_{group} [kN] (per pile)
Single pile	TS1	1	5.85	78	78 (78)
Single pile	TL1	1	6.85	79	81 (81)
Single pile (rusty)	TLR1	1	6.85	72	77 (77)
Two piles	TL2	2	6.85	73	170 (85)
Two piles	TL2X	2	6.85	38	97 (48.5)
Three piles	TL3	3	6.85	69	240 (80)
Six piles	TS6	6	5.85	55	340 (56.7)
Twelve piles	TL12	12	6.85	67	820 (68.3)

Considerable variation in $Q_{install}$ (+/- 35%) is evident and could be due to site variability since there is a trend of lower resistance on the east side of the site. Rainfall-induced changes in pore pressure may have been an additional influence. The test programme was conducted during the monsoon season, consisting of hot dry conditions interspersed with heavy rain. Byrne & Randolph (2003) and Lehane et al (2003) report significant changes in pile capacity and CPT resistance due to seasonal pore water effects.

4.2 *Single pile load tests*

Notably high stiffness was observed during the 3 single pile load tests. Plunging failure at a load of 77-81 kN occurred at a settlement of 3 mm (3% D) (Figure 4). The curious result that the 5.85 m and 6.85 m piles have equal capacity arises because q_c decreases between 5.5 and 7 m depth (Fig. 2). The installation force, $Q_{install}$, is recovered in each load test. Therefore, in these sandy ground conditions, installation force provides a good indication of plunging capacity, suggesting that the jacking process is drained.

The plunging loads are in broad agreement with predictions from design methods by the MTD (Jardine & Chow 1996) (average discrepancy 5%). The MTD method has been modified to assume that $q_{bf}=q_c$, rather than for q_{bf}/q_c to reduce with increasing pile diameter. This approach follows White & Bolton's (2005) analysis of a database of closed-ended piles and agrees with field measurements by Chow (1997) and Lehane (1992). The open-ended piles used in these tests were plugged during the final installation stroke as well as the load tests, so have been treated as if closed-ended.

Load transfer back analysis using RATZ and the modified MTD profile of ultimate capacity was conducted. Good agreement between the measured and calculated head response is found when the parabolic τ_s-z response is based on $G_{oper}=G_0/2$ (where G_0 is found from q_c following Baldi et al (1989)) and the base response is modelled with w_{bf}= 3.5 mm (Figure 4). The locking-in of residual load was also modelled within RATZ, leading to $q_b=0.72q_c$ at the start of the load test.

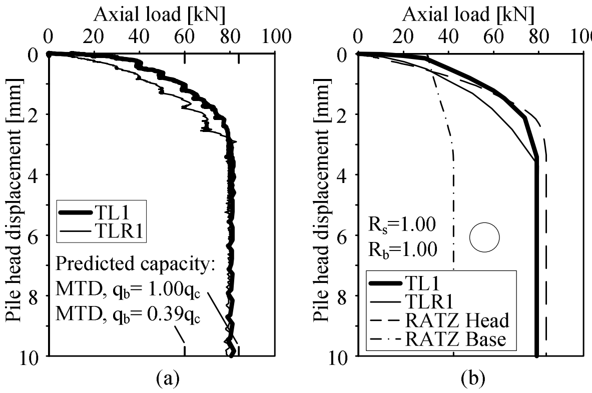

Figure 4. Load-settlement response of single piles

4.3 *Pile group load tests*

The pile groups were less stiff than the single piles, although 90% of the plunging load was reached before a settlement of 10 mm (10% D), even for the group of 12 piles (Fig. 5). A group strength efficiency, $\zeta_{strength}$ (Equation 1), close to unity is apparent in every case, indicating that each pile re-mobilises the installation force of the first pile, $Q_{install,}$ when failed.

$$\zeta_{strength} = \frac{Q_{group}}{nQ_{install}} \tag{1}$$

Comparison of the single pile and pile groups is hampered by the variation in pile strength evident from the installation force (Fig. 3). To eliminate this variability in the RATZ back-analyses of the pile groups, the q_c profile has been scaled in proportion to the ratio of $Q_{install}$ for the first pile in each group and for the single pile. Since τ_{sf} and q_{bf} are proportional q_c in the MTD design approach (which gave good predictions of the single pile capacity), this scaling accounts for variability between the tests in a simple manner. The scaling of q_c, and the inclusion of group interaction factors are the only differences between the RATZ analyses for the single piles and the pile groups.

The pile group RATZ analyses agree well with the measured response at typical working loads (<50% of the plunging load) (Fig. 5). These reasonable predictions of group settlement by applying a simple interaction factor approach to single pile load test results indicate that a spacing ratio of unity may not preclude the application of current simple design approaches.

The stiffness of the 12-pile group is over-predicted at high loads, possibly due to a different failure mechanism acting. The block of enclosed soil was observed to move downwards during failure, in the manner of a plug within a tubular pile.

5 DISCUSSION: STIFFNESS OF CONVENTIONAL PILES

The results from this investigation are summarised on Figure 6. Also shown are additional load test results for 100 mm diameter piles previously conducted at the same site (Yetginer et al 2003). All single piles recovered the jacking force from the final installation stroke when load tested. The groups of n piles recovered n times the installation force of the first pile, also at a low settlement, despite the spacing ratio of unity.

The stiffness of these jacked piles is considerably higher than conventional driven or bored piles. Existing guidance for the design of bored and driven piles is collated in Figure 7 and compared with the jacked pile results from this investigation and existing published data. The characteristic secant base stiffness, k_s, of the jacked piles at a settlement of 2% D is more than 2 and 10 times greater than recommended design values for driven and bored piles respectively.

It should be noted that in practice, tension cycles are applied to jacked piles that are installed using the type of machine shown in Figure 1, when each pile acts to provide reaction force. These cycles may eliminate any residual base load, and reduce the resulting head stiffness.

6 CONCLUSIONS

A series of field tests has been conducted on jacked piles and pile groups installed in sand. Axial load tests showed a stiff load-settlement response. The single piles reached plunging failure at a settlement of 3 mm (3% D). The groups of n piles reached 90% of plunging capacity (a load equal to n times the installation force of the first pile in the group) at a settlement of 10 mm (10% D) or less.

The load-settlement response of the single piles was well predicted by load-transfer analysis using parabolic τ_s-z and q_b-z models. The axial response of the pile groups was well predicted by modifying the single pile analysis using interaction factors based on elastic superposition. However, where the pile group comprised a closed cell, the stiffness was over-predicted and the pile cell and enclosed soil failed in unison.

If these observations are confirmed for a wider range of pile dimensions and ground conditions, the implications for the design of jacked piles in sand are that:

1. The measured jacking force during installation indicates the plunging capacity of the pile.
2. Jacked piles have a high base stiffness, due to the preloading of the soil below the base during installation, and the presence of residual base load.
3. Elastic superposition methods, combined with parabolic load transfer models, provide reasonable predictions of the response of a pile wall or group from the single pile response, even when the piles are installed at a spacing ratio of unity.

The stiffness of these jacked piles exceeds typical recommended design stiffnesses for driven and bored piles by factors of more than 2 and 10 respectively. Since pile design is usually governed by serviceability and stiffness, jacked piles offer the potential for significantly improved design efficiency.

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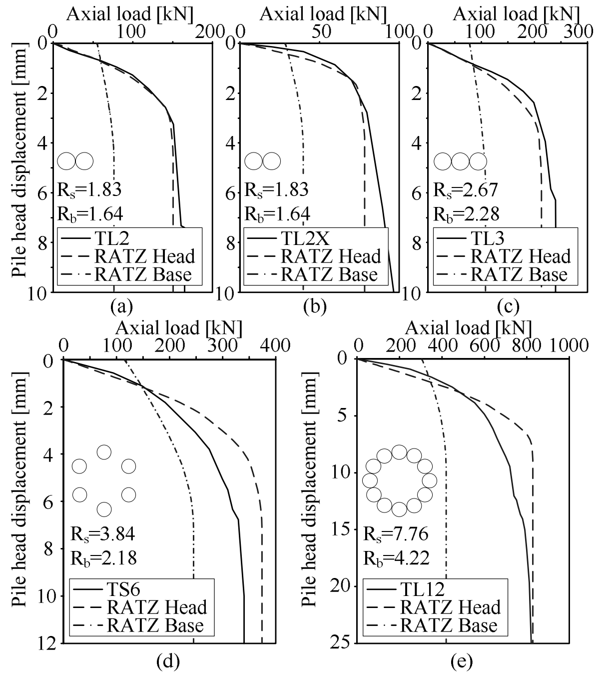

Figure 5. Load-settlement response of pile groups

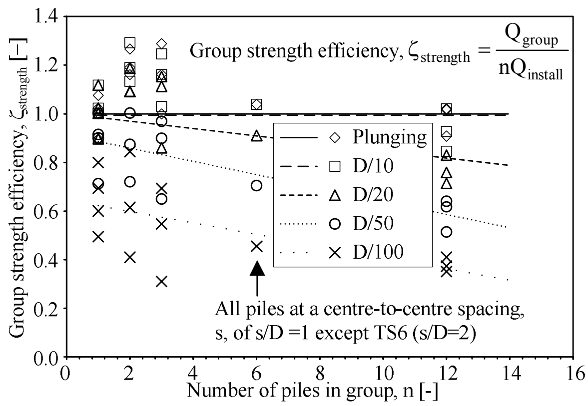

Figure 6. Recovery of installation force during load tests

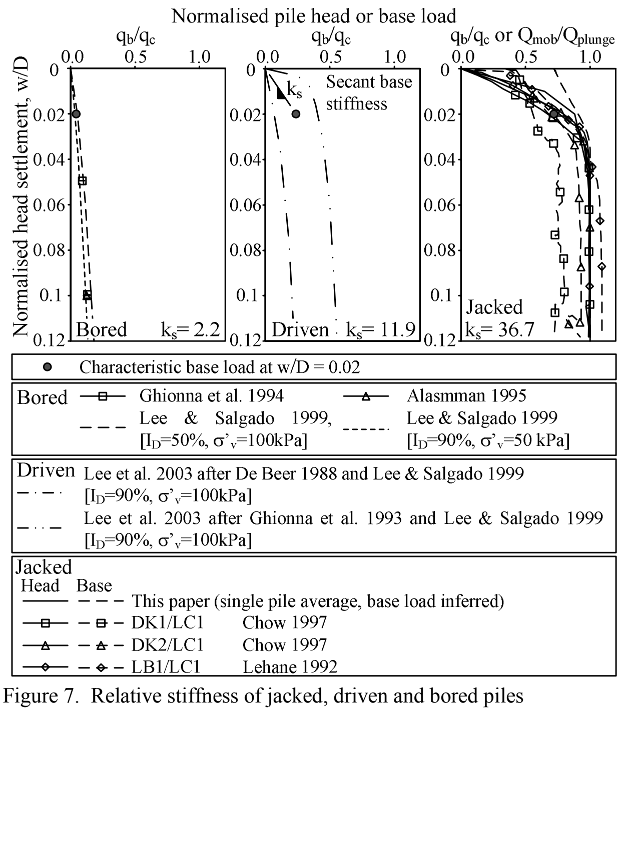

Figure 7. Relative stiffness of jacked, driven and bored piles