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A novel urban foundation system using pressed-in H-piles

Un nouveau système de fondation utilisant des pieux à section en H installés par fonçage

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ABSTRACT: A novel foundation system comprising steel H-piles is described. Using the press-in method, continuous walls of H-piles can be installed without significant environmental disturbance. Maintained load tests show a high positive group effect, indicating that the strength of the completed foundation exceeds the sum of the installation force of the individual piles. This construction technique represents an efficient foundation solution for urban areas.

RESUME: Un nouveau système de fondation utilisant des pieux en acier à section en H est décrit dans cet article. Grâce à la méthode de fonçage, des parois continues de pieux à section en H peuvent être installées avec un impact moindre sur l'environnement. Des essais sous charge constante ont montré un effet de groupe très favorable, duquel découle un rapport intéressant entre la résistance de la fondation en service et la force nécessaire à l'installation des pieux. Ce système permet une solution efficace pour les zones urbanisées.

1 INTRODUCTION

The press-in method of pile installation is a modern technique by which pre-formed piles can be hydraulically jacked into the ground with minimal noise or vibration compared to conventional dynamic methods. This technique permits the installation of displacement piles in the modern urban environment, without causing damage to existing structures or human disturbance. Measurements of ground vibrations close to press-in piling operations indicate that pile installation can continue within 2 m of residential buildings without Eurocode 7 vibration limits being exceeded (White et al., 2002). Opportunities now exist to use displacement piles, jacked into the ground using the press-in method, as an alternative to bored piling techniques. This paper discusses an application of the press-in method in which a novel arrangement of H-piles is used to maximize the axial capacity of the completed foundation, whilst allowing the substructure to be installed using a small and unobtrusive press-in piling machine. Field tests conducted during the design of the 'Daido Shinagawa' building, in Tokyo, Japan, are presented and analysed.

2 BACKGROUND

The press-in installation technique uses the negative shaft friction of previously-installed piles to provide reaction force, allowing higher jacking force to be mobilized compared to jacking techniques which rely on mobile kentledge. The press-in piling machine 'walks' along the pile wall, gripping previously-installed piles whilst manipulating the next pile. Although originally designed for sheet pile installation, press-in piling is increasingly being considered for the construction of axially-loaded foundations. One perceived drawback of this application is that the press-in technique requires piles to be installed in a continuous row. The machine cannot 'reach' far from previously-installed piles when jacking the next. Conventional design methods (e.g. BS8004, 1986) forbid the installation of axially-loaded piles at a centre-to-centre spacing of less than two pile diameters, to avoid the possibility of a low group effect (i.e. the capacity of *n* piles being less than *n* times the capacity of a single pile).

However, this paper demonstrates that continuous rows of H-piles should be considered differently to conventional groups of closely-spaced tubular piles. Figure 1a shows an HP-150 press-in piling machine, capable of installing 400 x 400 mm section H-piles in continuous rows, with a maximum jacking force of 1500 kN. Precise manipulation of the robotic 'chuck' allows the separation between adjacent H-piles to be maintained below 5 mm. The completed wall consists of square box-sections. By considering the equilibrium of a soil element within the pan of an H-pile during installation and subsequent loading, it can be shown that significantly higher shaft friction will be available under working conditions. During installation, shaft friction, τ_s, acting downwards on the soil element within the pile pan, is balanced by upwards shear stress, $\lambda\tau_s$, within the adjacent soil, governing the distribution of vertical stress, σ'_v, within the pile pan (Figure 1b). Vertical equilibrium leads to a relationship with the general form of Equation 1. Equation 1 can be combined with Coulomb's Law (Equation 2), by introducing an earth pressure coefficient, *K*, and interface friction angle, δ. Integration of Equations 1 and 2 predicts vertical stress (and therefore shaft friction) within the pan of a single H-pile to increase with depth as a gentle exponential, reflected in the low value of the exponential parameter *A* (White, 2002).

When the completed H-pile wall is loaded in unison, all sides of the soil element within the pile pan are dragged downwards by shaft friction (Figure 1c). The vertical equilibrium equation predicts shaft friction to evolve as a strong exponential function of depth, reflected in a larger value of the parameter *A*. Shaft friction within the closed box-sections created by adjacent H-piles is mobilized in a similar manner to the internal shaft friction of tubular piles, which can be analysed through vertical arching (silo) theory. Randolph et al. (1991) and White et al. (2000) discuss the very high internal shaft friction that can be mobilised through vertical arching.

$$\frac{d\sigma'_v}{dz} = A\sigma'_v + \gamma' \tag{1}$$

$$\tau_s = K\sigma'_v \tan\delta \tag{2}$$

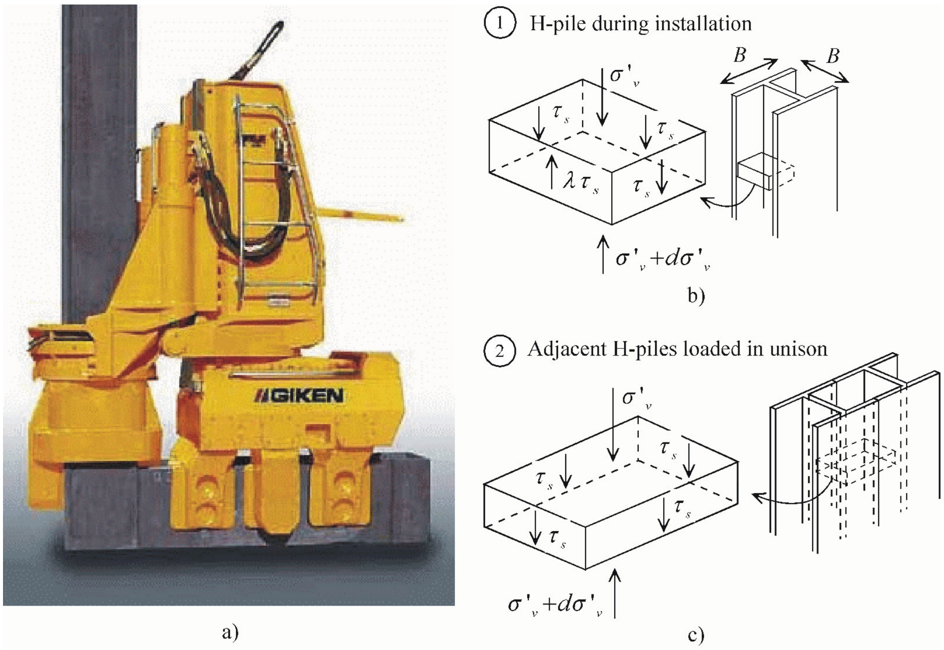

Figure 1. a) Press-in piling machine for installing H-piles b) Vertical force equilibrium during installation of an H-pile c) Vertical force equilibrium during loading of an H-pile wall

3 SITE DESCRIPTION

The analysis described above indicates that by pressing in adjacent H-piles, vertical arching and high internal shaft capacity can be activated after installation (Figure 2). Field testing was conducted to investigate the resulting positive group effect. The test site is located in Shinagawa-ward, Tokyo. The ground conditions and arrangement of test piles are shown in Figure 3. The stratigraphy consists of layers of fill, silt and sand and gravel overlying Tokyo mudstone. Laboratory tests on the Tokyo mudstone indicated an unconfined compressive strength in the range 2.4 – 2.7 MPa.

A row of 400 mm × 400 mm H-piles was installed using a Giken Seisakusho HP-150 press-in piler. The row consisted of 23 shallow H-piles, terminating above the mudstone bearing stratum. Interspersed with these shallow piles, and protruding down into the bearing stratum, were the test piles (Figure 3). The test piles were instrumented with strain gauges at 6 locations along their length, to allow the load distribution to be deduced. However, due to space restrictions, only the pile head load-settlement response will be discussed in this paper.

A total of four load tests were carried out, of which test nos. 1, 3 and 4 were on piles installed to a depth of 20 m, penetrating 0.9 m into the bearing stratum. Test no. 1 consisted of a single pile. Test nos. 3 and 4 consisted of two and three adjacent piles respectively. These pile walls were loaded concurrently via a metal loading plate. Reaction force during the load tests was provided by tensile loading of two walls of 15 m deep sheet piles located 2 m distant on either side of the H-pile row. The load tests were conducted between 14 and 20 days after installation of the piles.

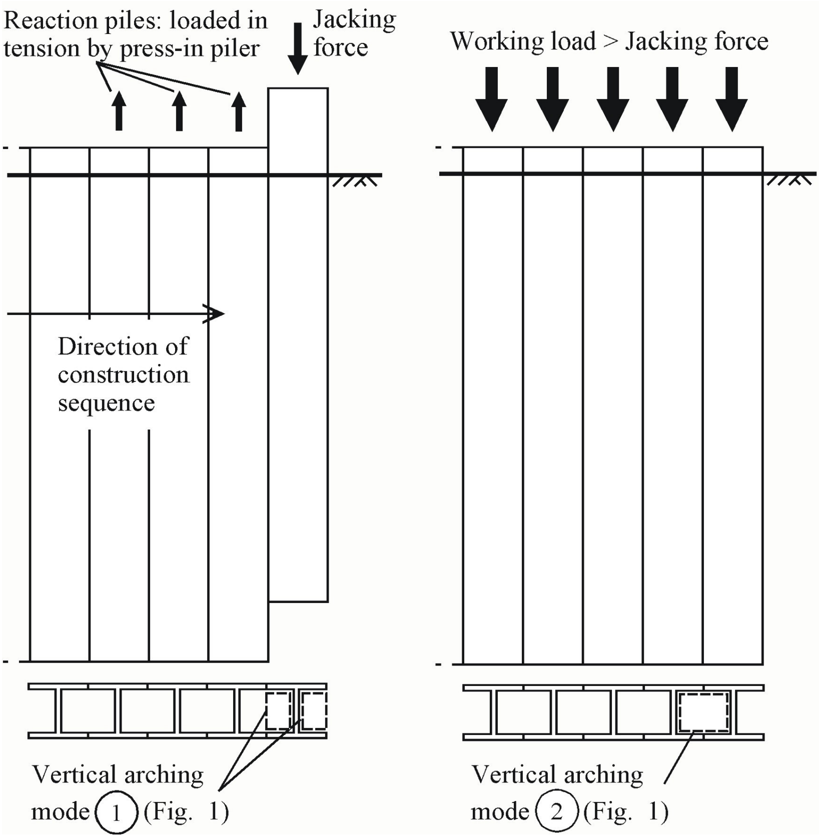

Figure 2. A construction sequence in which vertical arching is activated after installation

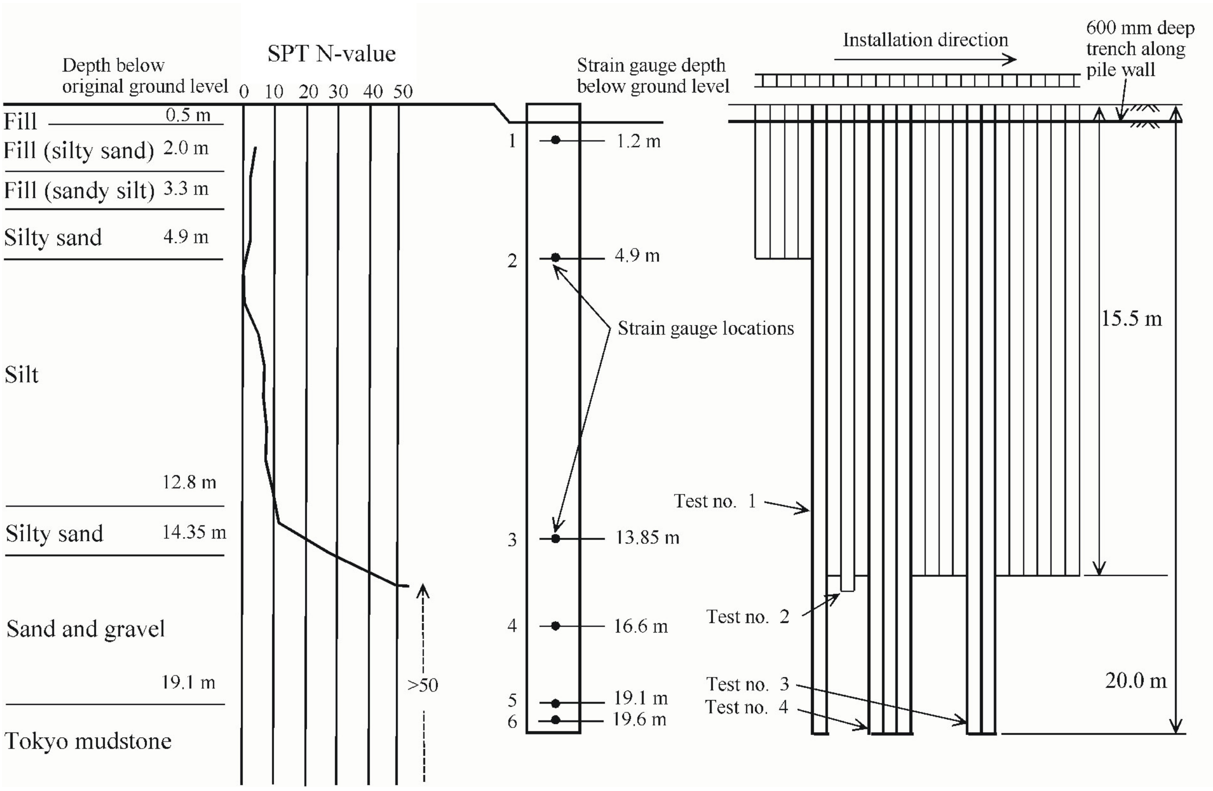

Figure 3. Ground profile and arrangement of test piles

4 TEST RESULTS

The mean force required to jack the 6 test piles to the final embedded depth of 20 m was 869 kN, with a standard deviation of 95 kN (Table 1). The pile head load-settlement response of each test is shown in Figure 4a, with the load expressed per pile. The failure loads, according to a settlement criterion of $B/10$ (40 mm) are listed in Table 1. Two key conclusions are evident. Firstly, the capacity of a single pile exceeds the installation force. 'Set-up' is evident, with the capacity of the single test pile exceeding the mean installation force by 37%. Secondly, the capacity of a wall of n piles is greater than n times the capacity of a single pile, as predicted by vertical arching. A positive group efficiency, ζ_{group}, defined according to Equation 3, of around 1.5 is evident. It should be noted that efficiency factor, ζ_{group}, is defined by comparing the pile group capacity with the load test capacity of a single pile, not the installation force. This definition isolates geometric group effects from set-up.

This positive group effect is in contrast to predictions using conventional theory. Firstly, it would be expected that a single pile in a wall of H-piles would have lower shaft capacity when loaded simultaneously with its neighbour since the area of the failure surface is reduced. Conventional theory would apply shaft friction to the perimeter of the H-pile wall. This perimeter has a length less than the sum of the perimeter of the individual piles.

Secondly, it is usually expected that the efficiency of a pile group with a low spacing ratio is close to or less than unity. Laboratory test data has suggested that a positive group effect occurs at spacing ratios of 2-6 due to compaction and stress-increases during group installation. However, this effect appeared to reduce to unity at a spacing ratio of 1, as used in these field tests (Vesic, 1969). Also, when failure is defined by a settlement criterion, an efficiency of less than unity is predicted by considering the superposition of elastic settlement troughs or the interaction of neighbouring stress fields (Fleming et al., 1992; Poulos & Davis, 1980).

An alternative method of quantifying the efficiency of an H-pile wall is to consider the capacity offered by each enclosed pile compared to the jacking force of a single pile. Test nos. 3 and 4 consist of an ‘end’ pile and 1 and 2 ‘enclosed’ piles respectively, if each pile wall is sub-divided geometrically as shown in Figure 4b. The capacity of walls of *n* and *n*+1 piles can be compared to deduce the contribution of an additional ‘enclosed’ pile (Table 1). The resulting wall performance factor, $\zeta_{wall,set\text{-}up}$, is defined according to Equation 4.

The term ‘performance’ instead of ‘efficiency’ is used to describe the factor $\zeta_{wall,set\text{-}up}$, to indicate that the enclosed pile capacity has been normalized by the installation force, $Q_{installation}$, rather than the single pile capacity, Q_{single}, thus including the effect of ‘set-up’. This performance factor, $\zeta_{wall,set\text{-}up}$, provides a simple link between the press-in installation force (which must be minimized to improve driveability and can be measured during construction) and the wall capacity (which must be maximized to improve foundation strength, and validated for quality assurance).

Values of $\zeta_{wall,set\text{-}up}$ in the range of 2.07-2.57 are recorded, indicating that the contribution of each ‘enclosed’ pile is more than twice the jacking force required for installation. Some insight into the source of this additional capacity is provided by the distribution of shaft friction during the load test. Strain gauge measurements show a concentration of shear stress on the lower part of each pile wall. In contrast, the single pile shows only a gentle increase in shaft friction close to the pile tip. This concentration of shear stress is indicative of the mobilisation of high internal shaft friction within the enclosed pile sections, in agreement with the vertical arching analysis described above.

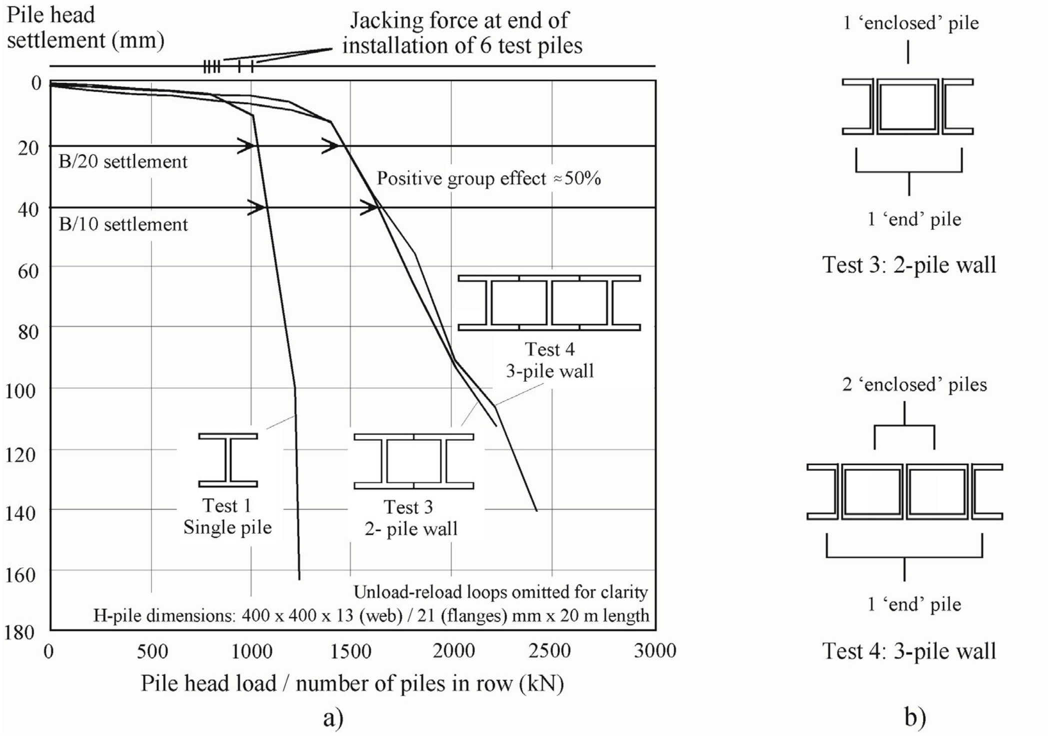

Figure 4. a) Load-settlement response of test piles b) Division of pile walls into ‘end’ and ‘enclosed’ sections

Table 1. Shinagawa load tests results

Test	*No. 1*	*No. 3*	*No. 4*
Installation load(s) (kN)	780	844; 1012	804; 810; 962
	Mean value, $Q_{installation}$ = 869 kN		
Load at failure (*B*/10 settlement) (kN)	1070	3300	5100
‘Set-up’ ratio	1.37	-	-
Group efficiency, ζ_{group}, (after set-up, Eq^{n} 3)	-	1.54	1.59
Contribution of extra ‘enclosed’ pile (kN)	-	2230	1800
Wall performance factor, $\zeta_{wall,set\text{-}up}$ (Eq^{n} 4)	-	2.57	2.07

$$\zeta_{group} = \frac{Q^{n}_{wall}}{nQ_{single}} \tag{3}$$

$$\zeta_{wall,set-up} = \frac{Q^{n+1}_{wall} - Q^{n}_{wall}}{Q_{installation}} \tag{4}$$

5 DISCUSSION

These results shows that the strength of an H-pile wall is considerably greater than the sum of the jacking force required for installation. Vertical arching within the soil column created by the installation of adjacent H-piles leads to a significant increase in capacity. Also, a contribution of time-induced 'set-up' to the increased capacity has been measured. These results demonstrate that a relatively small (150 tonne) capacity press-in piler can be used to construct deep foundations capable of supporting heavy structures. The range of values shown in Table 1 suggests that when designing to a failure criterion of B/10 settlement, a value of $\zeta_{wall,setup} = 2.0$ is appropriate for extrapolating to the capacity of a complete ring of H-piles at the Shinagawa site. This capacity represents a load of 1738 kN applied to each H-pile, which corresponds to a stress of 11 MPa carried down to the underlying mudstone (ignoring external shaft friction).

The 9-storey Daido Shinagawa building currently under construction at the test site is supported on two 19.2 m diameter rings of H-piles of the type used during this test programme. By using the novel construction technique described in this paper, the substructure has been constructed with minimal environmental disturbance.

6 CONCLUSIONS

A novel foundation system comprising adjacent H-piles has been evaluated. Using the press-in method, continuous walls of H-piles can be installed by jacking, without significant environmental disturbance. During installation of a single H-pile, the resistance acting on the open pile section is low. When the completed pile wall is loaded the adjacent piles act as closed box sections, with a resulting increase in capacity.

The axial load capacity of a wall of adjacent H-piles has been investigated through a series of maintained load tests. A high positive group effect was recorded, indicating that the strength of the completed foundation exceeds the sum of the jacking force of the individual piles by a factor greater than two. This observation is in agreement with theoretical analysis of open and enclosed pile sections. This construction technique therefore represents an efficient foundation system, which can be installed in urban areas with minimal disturbance.

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