Settlement and load sharing of a piled raft with ground improvement on soft ground

Tassement et partage de charges d'une fondation mixte radier-pieux dans un sol meuble amélioré

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ABSTRACT
This paper offers a case history of design and performance of a seven-story building of a piled raft on loose sand underlain by soft silt layers. In order to reduce consolidation settlement of the soft silt and to cope with the liquefiable loose sand, a piled raft combined with grid-form ground improvement was adopted. The design of the foundation was found appropriate by field measurements which concerned settlement, axial forces of the piles and earth pressures and pore-water pressure beneath the raft from the beginning of construction to the time about four years after the end of construction.

RÉSUMÉ
Cet article présente la conception et le comportement d'une fondation mixte radier-pieux d'un bâtiment à sept niveaux. Cette fondation est construite dans une couche de sable lâche reposant sur des couches de limon. Ce type de fondation a été adopté en combinaison avec l'amélioration, en forme de quadrillage, d'une partie du sol meuble et ce, afin de réduire le tassement de la couche de limon et contenir les effets induits par la couche de sable lâche à fort potentiel de liquéfaction. L'article discute le comportement de cette fondation sur la base d'une série de mesures sur site, qui se poursuivent pour la quatrième année depuis le début de la construction du bâtiment. Le dimensionnement de cette fondation est estimé convenable considérant les mesures de tassement, des forces axiales sur pieux, des contraintes sur le sol et de la pression de l'eau interstitielle sous le radier.

Keywords : piled raft, ground improvement, settlement, load sharing, monitoring

1 INTRODUCTION

In recent years there has been an increasing recognition that the use of piles to reduce raft settlements can lead to considerable economy without compromising the safety and performance of the foundation (Poulos, 2001). In Japan piled rafts have been used for more than 80 buildings since it was first applied to the four-story building in Urawa (Yamashita & Kakurai, 1991; Yamashita et al., 2008). However there exist not so many case histories on monitoring load sharing between raft and piles as well as settlement. Thus accumulation of field evidences by monitoring full-scale structures is required to develop more reliable design method (Mandolini et al., 2005).

This paper offers a case history of design and performance of a piled raft on loose sand underlain by soft silt layers. In order to reduce consolidation settlement of the soft silt and to cope with the liquefiable loose sand, a piled raft combined with grid-form ground improvement was adopted. To confirm validity of the foundation design, field measurements were performed on the settlement, axial forces of the piles, earth pressures and pore-water pressure beneath the raft from the beginning of construction to the time about four years after the end of construction.

Photo 1. Seven-story office building in Minamisuna.

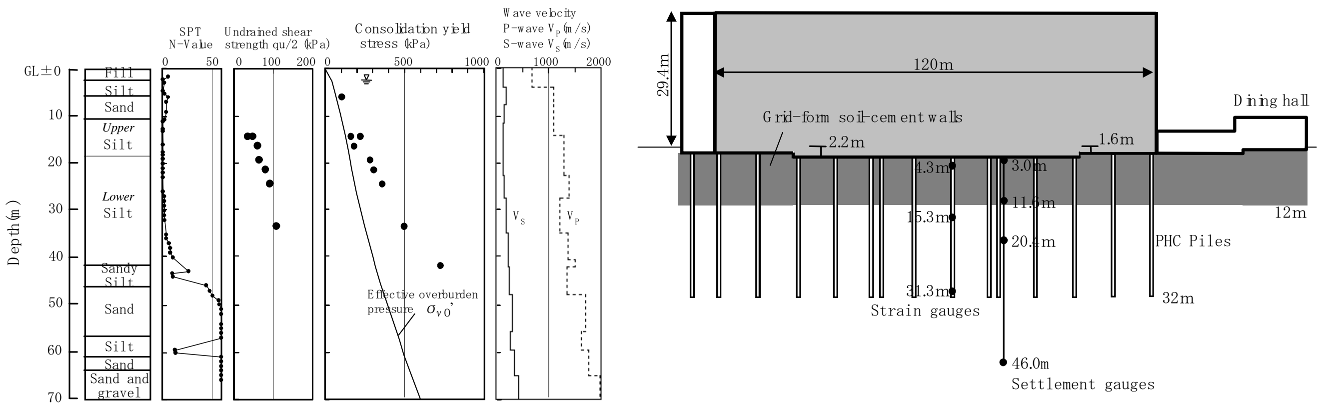

Figure 1. Schematic view of the building and foundation with soil profile.

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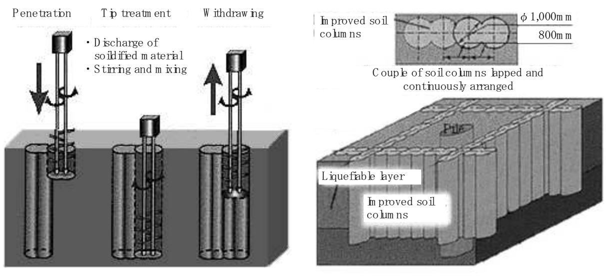


Figure 2. Grid-form ground improvement.

Photo 2. Grid-form soil-cement walls at the foundation level.

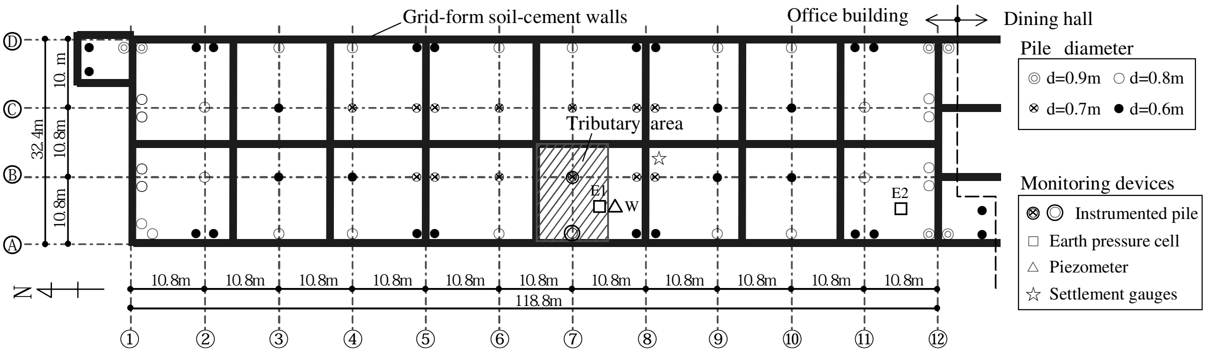


Figure 3. Layout of piles and grid-form soil-cement walls with locations of monitoring devices.

2 BUILDING AND SOIL CONDITION

The seven-story office building of 29.4 m in height above the ground surface with a flat dining hall is located in Minamisuna, Tokyo (Photo 1). The building is a steel-frame structure and a schematic view of the building and foundation with soil profile is shown in Fig. 1. The foundation levels are at depths of 2.2 m in central part and 1.6 m in both ends below the ground surface. The subsoil consists of an alluvial stratum to a depth of 46 m, underlain by a diluvial sandy layer of SPT N-values of 50 or more. The soil profile down to a depth of 11 m is made of soft silt and loose sand. Between depths of 11 m to 42 m below the ground surface, there lies a thick soft to medium silt stratum. The upper silt layer between depths of 11 m to 18 m is slightly overconsolidated with an overconsolidation ratio (OCR) of about 1.1. The lower silt layer between depths of 18 m to 42 m is overconsolidated with an OCR of 1.8 or more.

3 FOUNDATION DESIGN

3.1 *Ground improvement*

It appeared that the loose sand between depths of 6m to 11 m has a potential of liquefaction during earthquakes of the maximum horizontal ground-surface acceleration over 200 Gal, according to the simplified method (Tokimatsu and Yoshimi, 1983). To cope with the liquefiable sand layer, a grid-form ground improvement was introduced. The grid-form soil-cement walls are constructed by deep mixing method as illustrated in Fig. 2 and the high-modulus soil-cement walls confine loose sand so as not to cause excessive shear deformation in the loose sand during earthquakes (Photo 2). The effectiveness of the grid-form ground improvement has become evident at the 1995 Kobe earthquake (Tokimatsu et al., 1996).

3.2 *Pile specification*

A total load in structural design is 378 MN which corresponds to the sum of dead load and live load of the building. The average contact pressure over the raft is 100 kPa with the local maximum of 142 kPa. If a raft foundation alone was used, more than 200 mm of consolidation settlement was predicted in the soft silt layers down to a depth of 18 m. In order to reduce the consolidation settlement and to ensure the differential settlements being below a tolerable amount, a piled raft was proposed. The piled raft was designed based on a design philosophy of "creep piling", i.e. sufficient piles are included to reduce the net contact pressure between raft and soil to below the consolidation yield stress of the clay (Hansbo, 1984; Jendeby, 1986). The allowable bearing capacity of each pile at a working condition was determined to be sufficiently larger than the load which should be carried by the pile based on the "creep piling". At the same time the design load of each pile should be smaller than the load at which significant creep starts to occur, at about 70 % of the ultimate bearing capacity. The piles were embedded in the lower medium silt layer enough to ensure the frictional resistance. Consequently a piled raft with the grid-form ground improvement was adopted which has a total number of 70 piles of 30 m in length, 0.6 m to 0.9 m in diameter. The piles are pretensioned spun high-strength concrete (PHC) piles and were constructed by inserting a set of 15 m-long PHC piles into a pre-augered borehole filled with mixed-in-place soil cement to avoid noise and vibration. Figure 3 shows a layout of the piles and the grid-form soil-cement walls.

4 INSTRUMENTATION

The locations of the monitoring devices are shown in Fig.3. Two piles, 7A and 7B, were installed with a couple of LVDT-type strain gauges at pile head (at a depth of 4.3m). The pile 7B was installed with the other couples of strain gauges at depths of 15.3 m and 31.3 m. Earth pressure cells were installed at depths of 2.2 m (E1) and 1.6 m (E2) and a piezometer (W) was installed at a depth of 2.2 m beneath the raft. The vertical ground displacements below the raft were measured by settlement gauges. The settlements of the foundation were measured by an optical level. The reference point was set to an existing nearby building founded on end-bearing piles. The measurement of the axial forces of the piles, earth pressures and pore-water pressure beneath the raft and the vertical ground displacements started early in December 2003, at the time just before constructing steel reinforcement of the foundation slab.

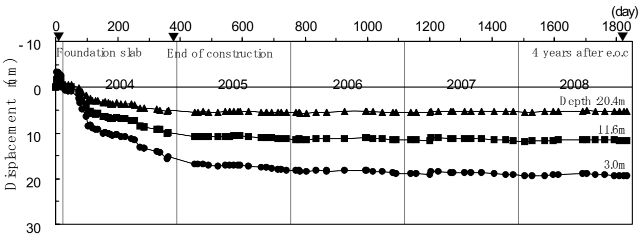


Figure 4. Measured vertical ground displacements.

The measurement of the foundation settlements began at the time just after concrete casting of the foundation slab.

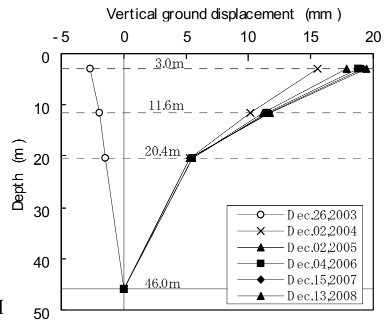


Figure 5. M lepth.

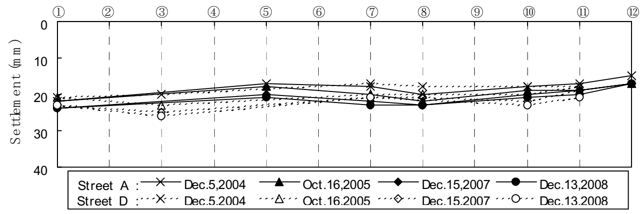
5 OBSERVATIONS

5.1 *Settlement of the foundation*

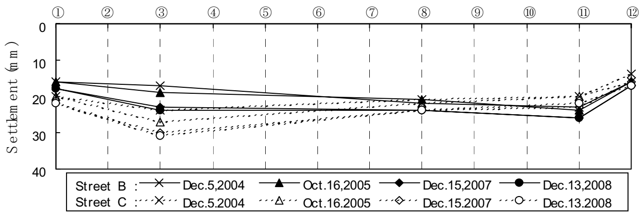
The building completed in mid-November 2004 and started in operation late in November. In this paper the measurement in Dec.2, 2004 are referred to as those "at the end of construction". Figure 4 shows the measured vertical ground displacements below the raft at depths of 3.0 m, 11.6 m and 20.4 m relative to a reference point at a depth of 46 m from the ground surface. The ground displacement at a depth of 3.0 m amounted to 15.6 mm at the end of construction. After that the displacement slightly increased and reached 19.4 mm in Dec.13, 2008, at the time about four years after the end of construction. Figure 5 shows the distributions of the measured vertical ground displacements with depth. At the time just before casting of the foundation slab (Dec.26, 2003), heaving of the ground due to the excavation amounted to 2.6 mm at a depth of 3.0 m. Considering the heaving the vertical ground displacement at a depth of 3.0 m amounted to 18.2 mm at the end of construction and reached 22.0 mm in Dec.13, 2008. Figure 6 shows the longitudinal settlement profile of the foundation measured by an optical level. The measured settlements were 14-24 mm at the end of construction. The settlements slightly increased to 17-31 mm in Dec.13, 2008 and the maximum inclination angle of the foundation amounted to 1/1200 radian between the columns 11B and 12B which is less than the serviceability limit of 1/1000 radian in structural design.

5.2 *Pile load, earth pressures and pore-water pressure*

Figure 7 shows the measured axial forces of the piles 7A and 7B. The measured values at pile head increased after the end of construction and reached a state of equilibrium on the pile 7A, but still slightly increased on the pile 7B at the time about four years after the end of construction. Figure 8 shows the distributions of the measured axial forces on the pile 7B. At the end of construction, the average skin friction between depths of 15.3 m to 31.3 m through the layers of soft to medium silt was 90 kPa whereas the value between depths of 4.3 m to 15.3 m through the layers of soft silt and loose sand was 23 kPa. The average skin friction in the lower part of the pile is consistent with the average undrained shear strength of the silt (81 kPa)

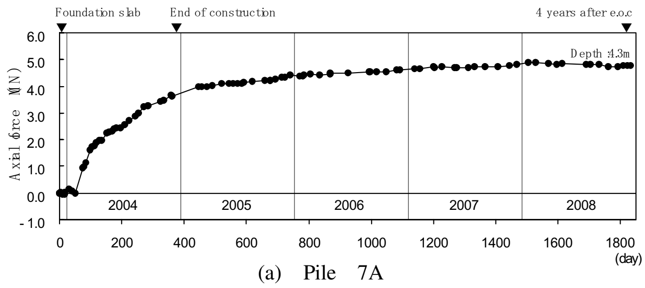


(a) Along the streets A and D

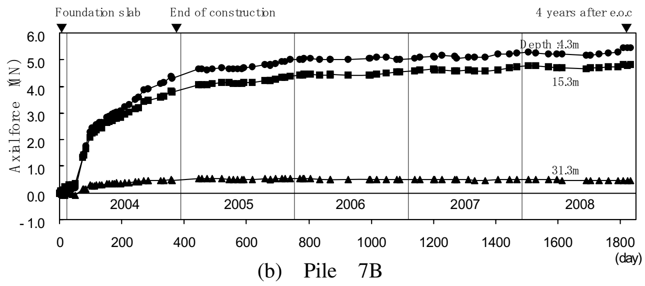


(b) Along the streets B and C

Figure 6. Measured longitudinal settlement profiles.



(a) Pile 7A



(b) Pile 7B

Figure 7. Measured axial forces of the piles 7A and 7B.

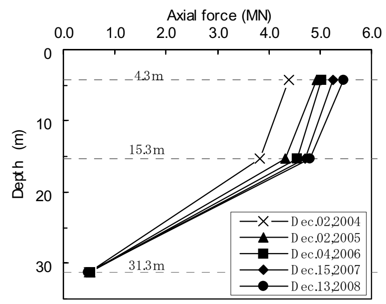


Figure 8. Measured axial force distribution on the pile 7B.

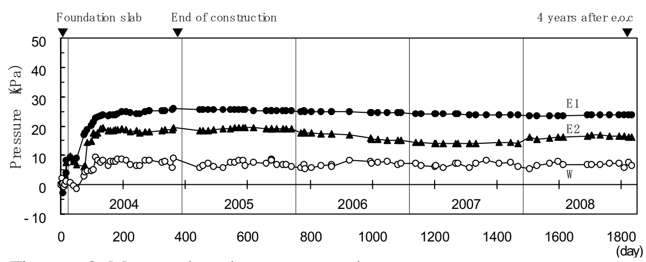


Figure 9. Measured earth pressures and pore-water pressure.

between depths of 15.3 m to 31.3 m. After that the skin friction in the lower part considerably increased and reached 123 kPa in Dec.13 2008, which is 52% larger than the average undrained shear strength. The skin friction in the upper part slightly increased after the end of construction. Figure 9 shows development of the measured earth pressures and pore-water pressure beneath the raft. The earth pressures seemed to reach constant values in early stage of construction despite of the successive increase in construction loading.

5.3 *Load sharing between raft and piles*

For piled rafts the equilibrium equation is expressed as follows:

$$W = W' + U_w = P_p + P_r' + U_w \tag{1}$$

where W is a total building load, W' is a net building load, U_w is buoyancy acted on the raft, P_p is pile resistance and P_r' is net raft resistance. The net raft resistance consists of the net resistance of soil and that of the grid-form soil-cement walls. On the tributary area shown in Fig.3, Eq.(1) can be expressed as follows:

$$W_t = P_{pt} + p_s'(A_t - A_p - A_g) + p_g' A_g + u_w(A_t - A_p) \tag{2}$$

where W_t is a total building load and P_{pt} is the sum of the pile-head load on the tributary area, p_s' is a net contact pressure between the raft and soil, p_g' is a net contact pressure between the raft and the grid-form soil-cement walls, u_w is a pore-water pressure beneath the raft, A_t is a tributary area, A_g is a plane area of the grid-form soil-cement walls and A_p is the sum of the cross-sectional area of the pile. Assuming that the total load applied to the foundation is constant after the end of construction and W_t is equal to the total load in structural design on the tributary area, the load sharing between raft and piles can be estimated by Eq.(2) with the measured values.

Figure 10 shows the time-dependent load sharing among the piles, soil, the soil-cement walls and the buoyancy on the tributary area. Table 1 shows the load-sharing ratios to the net building load at the end of construction and those at the time about four years after the end of construction. The ratio of the load carried by the piles considerably increased after the end of construction. On the other hand the ratio of the net load carried by the grid-form soil-cement walls to the net buiding load considerably decreased after the end of construction while the ratio of the net load carried by the soil slightly decreased after the end of construction. As for the raft-soil-pile interaction behaviour on the above, the following mechanism might be presumed: consolidation settlement occurred in the normally consolidated silt layer down to a depth of 6 m due to loading by the raft over the effective overburden pressure of the silt. The excessive load transferred to the soil-cement walls and this caused consolidation settlement in the upper silt layer with an OCR of about 1.1 just below the bases of the soil-cement walls. As a result a part of the load carried by the soil-cement walls gradually transferred to the piles.

Based on the results of monitoring on load sharing at the time about four years after the end of construction, it is known that the net load carried by the raft per unit area corresponds to 85% of the effective overburden pressure before excavation, i.e. the average pressure acted on the raft is close to the effective overburden pressure.

6 CONCLUSIONS

Long-term monitoring on settlement and load sharing of the piled raft with the grid-form ground improvement have been performed. At the time about four years after the end of construction, the measured settlements were 17-31 mm and the maximum inclination angle of the foundation was 1/1200 radian,

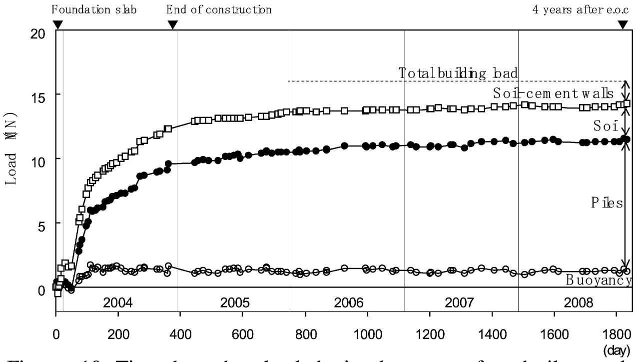


Figure 10. Time-dependent load sharing between raft and piles on the tributary area.

Table 1. Load sharing among piles, soil and soil-cement walls.

	At the end of construction (Dec.2, 2004)	4 years after the end of construction (Dec.13, 2008)
Ratio of load carried by piles to net building load $\alpha_p' = P_{pt} / (W_t - u_w (A_t - A_p))$	0.54 (0.50)*	0.69 (0.64)*
Ratio of net load carried by soil to net building load $\alpha_s' = p_s'(A_t - A_p - A_g) / (W_t - u_w (A_t - A_p))$	0.21	0.18
Ratio of net load carried by soil-cement walls to net building load $\alpha_g' = p_g' A_g / (W_t - u_w (A_t - A_p))$	0.25	0.13

*Values in parentheses are load-sharing ratios to total building load

which is less than the serviceability limit of 1/1000 radian. The ratio of the load carried by the piles to the net building load on the tributary area was estimated to be 0.69. This means that the average pressure acted on the raft corresponds to 85% of the effective overburden pressure before excavation. Consequently validity of the foundation design based on the "creep piling" is generally confirmed.

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