Performance of piled raft with grid-form DMWs supporting high-rise isolated building

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ABSTRACT

This paper offers a case history of a piled raft foundation with grid-form deep mixing walls (DMWs) supporting a 27-story intermediate-isolated residential building. The DMWs play the role of coping with liquefiable sand as well as improving the bearing capacity under horizontal and vertical loads, reducing a lateral ground displacement which acts on piles and a discrepancy between the predominant earthquake motion and the natural period of an isolated building. Field monitoring of the settlement and the load sharing was performed for over four years since the beginning of the construction. The measured settlement of the raft was about 12 mm and the ratio of the vertical load carried by piles was 0.84 to the total measured load, 0.66 to the design load. The ratio of the load carried by the DMWs was 0.097 to the total measured load. Consequently, it is confirmed that DMWs used in a piled raft work effectively to support a part of vertical load in liquefiable and soft ground.

Keywords: piled raft foundation, ground improvement, load sharing, settlement, intermediate isolated building

1 INTRODUCTION

A piled raft foundation is recognized to be a considerably economical foundation system to control settlement of the foundation to an acceptable level without compromising the safety and performance of the foundation by using piles as settlement reducers, and this type of foundation system was applied in various countries (Poulos, 2001, Katzenbach et al., 2000, and Yamashita et al., 2011). Recently, piled rafts were used for the foundations of Burj Khalifa in UAE, the world's tallest building of 828 m in height (Poulos and Bunce, 2008), and the tallest building in Japan with 300 m in height (Hamada et al, 2016). Furthermore, piled rafts were applied to very soft ground or liquefiable ground by improving the subsoil beneath the rafts to provide significant load capacity and prevent liquefaction. An advanced type of piled raft combined with grid-form cement deep mixing walls (DMWs) for improving subsoil was developed for application to real buildings, and the settlements and load sharing were measured (Yamashita et al., 2012; Yamashita et al., 2013; Yamashita et al., 2016).

This paper offers a case history of monitored settlements and load sharing results of a piled raft with DMWs supporting a 27-story intermediate-isolated residential building. The DMWs were used not only as countermeasures against liquefaction but also for improving the vertical load bearing capacity, resisting the lateral load from the inertial force of the superstructure, and reducing the lateral ground displacement which acts on piles and a discrepancy between the predominant earthquake motion and the natural period of the isolated building.

2 BUIDING AND SOIL CONDITIONS

Figure 1 shows schematic diagrams of side and top views of the monitored building with a representative soil profile which is located in Chiba Prefecture in Japan. The building is a residential building of an intermediate-isolated RC-frame structure, 27 story above the ground with a 1-story penthouse and a 1-story substructure, the total height of which is 103.2 m above the ground surface. The isolators were installed between the 3rd and 4th stories for improving the livability of the floors upper than the 3rd floor.

The subsoil consists of loam, tuffaceous clay, silty fine sand, clay, and silt to a depth of 13.57 m below the ground surface with shear wave velocity from 130 to 160 m/s. Below the layer, there lies a sand layer with N-values from 30 to over 50 and shear wave velocity of over 400 m/s.

3 FOUNDATION DESIGN

3.1 Liquefaction mitigation

The foundation level was at a depth of 6.75 m below the ground surface, and the ground water table appears approximately 2.85 m below the ground surface. Assessment of the potential for liquefaction during earthquakes was carried out using a simplified method based on N-values and fine fraction contents. It indicated that the silty sand from 4 to 10 m had a potential for liquefaction with the peak ground acceleration ("PGA") of 3.5 m/s^2. Therefore, to cope with the liquefiable silty sand and ensure the bearing capacity of the raft, grid-form DMWs were constructed from the foundation level to a depth of 15 m. Fig. 1 (b) shows a layout of piles and grid-form DMWs. The grid-form DMWs were designed using a simple lattice interval estimation method based on N-values, liquefiable sandy layer thickness and its depth (Taya et al., 2008). The ratio of the improved ground area to the original ground area is 0.21.

3.2 Design of piled raft

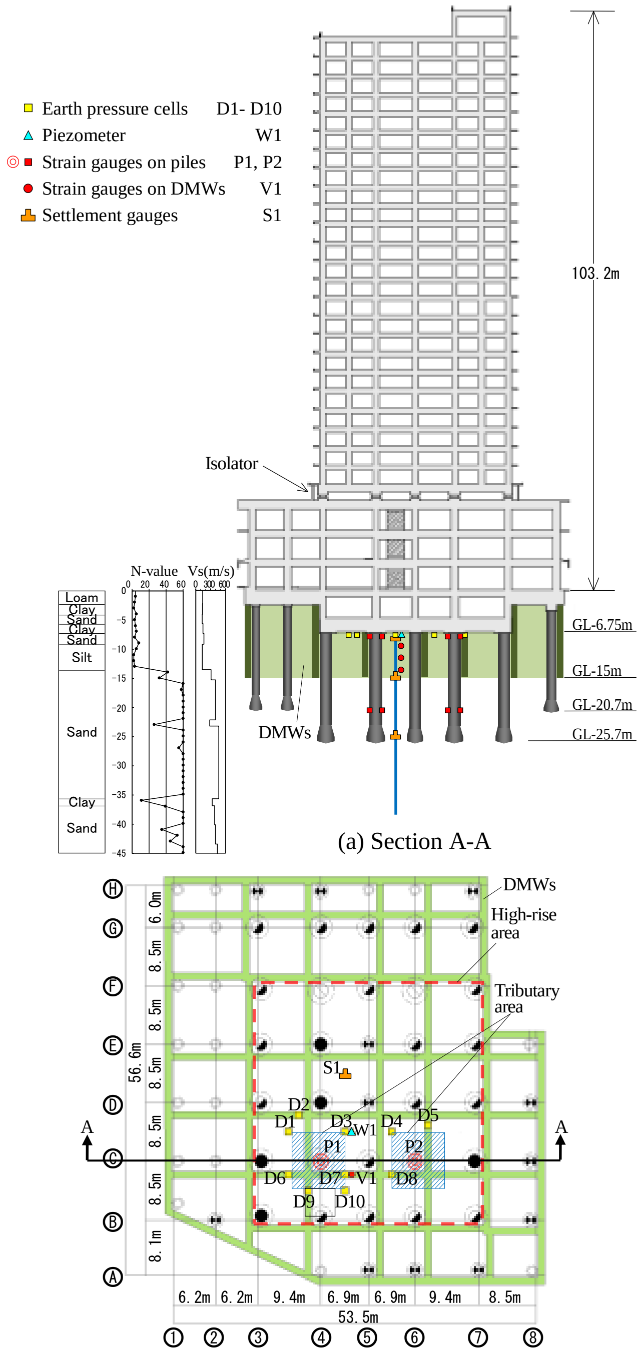
The piled raft foundation system consisting of cast-in-place concrete piles and grid-form DMWs was employed to support the vertical load and lateral load of the building during earthquakes. There lies clayey soil or sandy soil just below the raft at the N-value of around 5. Therefore, the original ground could not support the building without ground improvement. The total load in the structural design was 846.26 MN. The average contact pressure throughout the raft was 293 kPa, though it was 556 kPa around the high-rise structure area. Cast-in-place concrete piles from 1.8 to 2.2 m in diameter (enlarged to 3.3 to 3.9 m at their bottoms) in the high-rise area, from 1.2 to 1.6 m in diameter (enlarged to 1.7 to 2.3 m at their bottoms) in the low-rise area, were used to reduce the settlement to an acceptable level (see Fig. 1).

In the seismic design of the piles, the shear forces and bending moments of piles were estimated by the analytical method, considering the interaction between piles and raft friction (Hamada et al., 2015). The raft friction was estimated from the estimated/ assumed vertical load sharing of the raft and water pressure acting on the raft. Since the result value was not enough for the design lateral load on the raft, the design lateral loads on the piles were estimated considering the slip mode of the raft. To meet the aseismic design criteria, the bending moments and shear forces of piles are less than the ultimate limit sectional forces against large earthquake motions, the recurrence interval of which is approximately 500 years.

3.3 Design of grid-form deep mixing wall

The DMWs were applied not only as countermeasures against liquefaction at a silty fine sand layer down to 10 m below the ground surface, but also for supporting the building loads, resisting the inertial force of the superstructure during earthquakes, and reducing the lateral ground displacement acting on piles and a discrepancy between the predominant earthquake motion and the natural period of the isolated building. The compressive strength in designing the soil-cement was 2.0 MPa. The DMWs reached the bearing layer down to a depth of 15 m below the ground level.

In the seismic design of the grid-form DMWs, only the longitudinal walls in a plane direction were considered to resist the lateral inertial force of the building and the inertial force of the soil enclosed by the DMWs, which means that the transverse walls were



(a) Section A-A

(b) Layout of piles and DMWs

Fig. 1. Location of monitoring devices with soil profile.

ignored in terms of resistance elements, judging from a difference in lateral stiffness.

4 INSTRUMENTATION

To confirm the validity of the foundation design, the foundation settlement and the load sharing between piles and raft were measured for the period from the beginning of the construction to 26 months after the end of the construction (E.O.C.). Fig. 1 shows the locations of the monitoring devices.

Two piles (P1 and P2) with a diameter of 2.2 m (the bottoms enlarged to 3.9 m) were provided with a couple of LVDT-type strain gauges at a depth of 7.85 m (near the pile heads) and a depth of 17.85 m near the pile toes) as shown in Fig. 1(a). Near the instrumented piles, ten earth pressure cells and one piezometer were installed beneath the raft at a depth of 6.95 m. The vertical ground displacements below the raft were measured by differential settlement gauges. LVDT-type transducers were installed beneath the raft at depths of 7.85 m, 14.75 m and 25.9 m to measure the displacements relative to the reference point at a depth of 39.9 m of dense sand as shown in Fig. 1.

5 RESULTS OF MONITORING

5.1 Settlement

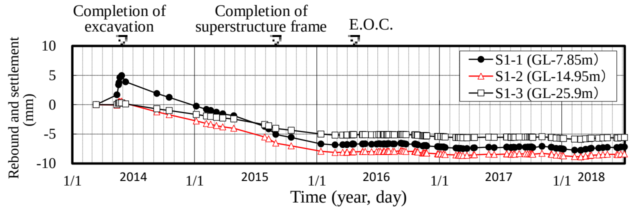
Figure 2 shows the vertical ground displacements vs. time measured by the differential settlement gauges, where a positive sign means a rebound. The rebounds were generated as the excavation of the basement construction proceeded, and a maximum rebound of 5 mm was measured at a 7.85 m depth by excavation of 6.75 m of the ground. After the end of the excavation, settlement occurred in response to the subsequent load. Fig. 2 (b) shows the initialized ground displacements after completion of the excavation. The initialized ground displacement was approximately equal to the settlement of the 'piled raft'. The settlement of the piled raft reached 11.8 mm at the end of the construction and thereafter, slightly increased to 12.2 mm and became stable at 26 months after the E.O.C.

5.2 Pile load

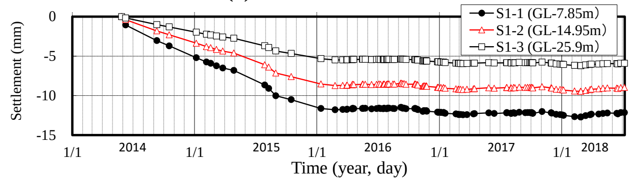
Figure 3 shows the development of the measured axial loads of Piles P1 and P2, where the axial loads were calculated hypothetically by Young's modulus of concrete, the result of which was 21.0 GPa. The pile-head loads were 18.0 MN for P1 and 17.9 MN for P2 at the E.O.C. These loads slightly increased after that and reached 21.5 MN and 22.4 MN for P1 and P2, respectively, at 26 months after the E.O.C. From the difference between the axial forces at the pile heads (GL-7.85 m) and the pile toes (GL-17.85 m), the mobilized frictional resistance (average skin friction around the piles between GL-7.85 m and -17.85 m) was estimated to be 114 kPa and 93 kPa for P1 and P2, respectively. It is considered that the values were relatively small because the displacements of the piles relative to the ground were small due to the existence of raft and DMWs. Hence, the ratios of the axial forces at the pile toes to those at the pile heads were about 0.63 for P1 and 0.71 for P2, respectively. Those values were relatively large.

5.3 Contact pressures of raft

Figure 4 shows the development of the measured contact pressures between the raft and the soil, together with the pore-water pressures beneath the raft. The measured contact pressures between the raft and the DMWs (D2, D5, D7 and D8) were higher than those

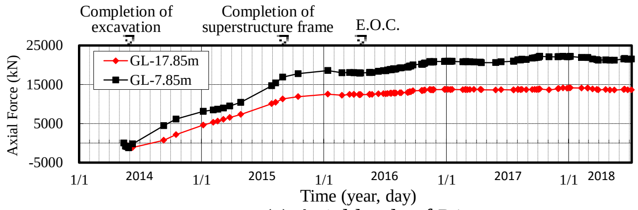


(a) Rebound and settlement

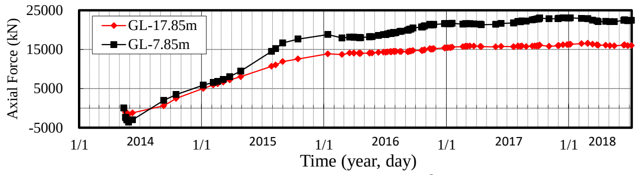


(b) Settlement after excavation

Fig. 2. Measured vertical ground displacements below the raft.



(a) Axial loads of P1



(b) Axial loads of P2

Fig. 3. Measured axial loads of piles.

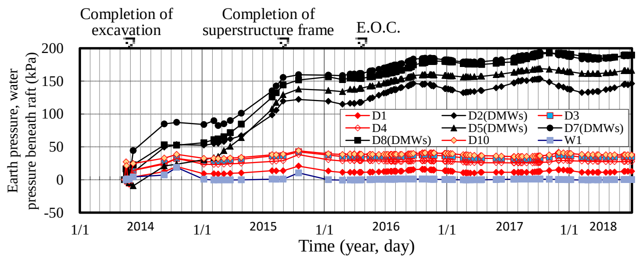


Fig. 4. Contact pressures and pore-water pressures beneath raft.

between the raft and the soil as expected. The measured contact pressures at the soil were 10 to 40 kPa, whereas the pressures at the DMWs were 140 to 190 kPa at 26 months after the E.O.C., which were about 5 times those at the soil. These values vary seasonally but are almost stable. The pore-water pressure was almost 0 kPa.

5.4 Strains on Soil Cement Walls (DMWs)

Figure 5 shows the development of the measured strains on the DMWs. The tension strains (positive values) occurred due to the ground rebound, and the compression strains (minus values) were increasing with the increase of the building weight.

Though the measured strains at GL-7.5 m were smaller than those at the deeper points, that seems to have been affected by the improper installation of the gauge at GL-7.5 m. The axial compression stress caused at the DMWs is estimated to be 168 kPa, hypothetically, when the axial strain is 210 micro, and the Young's modulus of the DMWs is 800 MPa. The estimated value 168 kPa corresponds to the measured contact pressure of the DMWs shown in Fig. 4.

5.5 Load sharing between piles and raft

Figure 6 shows the time-dependent load sharing among the piles, DMWs, soil and buoyancy, which are all in the tributary areas of two Columns P1 and P2 shown in Fig. 1 (b). Here, the shared loads carried by the soil were calculated, multiplying the measured average contact pressures of D3, D4 and D10 by the corresponding tributary areas, and the shared loads carried by the DMWs were calculated by averaging the contact pressures of D7 and D8 which were multiplied by the tributary areas of the DMWs respectively, where the tributary area of P1 and P2 is 138.56 m^2 (8.15 m× 8.5 m×twice), the DMW area is 26.86 m^2, the soil area is 104.08 m^2 and the piles' sectional area is 7.6 m^2 (for two piles). The load supported by the DMWs was estimated to be 5.08 MN (189 kPa×26.86 m^2), the load of the soil was 3.47 MN (33.3 kPa×104.08 m^2), and the total load including the measured pile-head loads (44.0 MN) was 52.5 MN, which was smaller than 66.4 MN, the sum of the two design column loads (33.9 MN and 32.5 MN), which, however, can be said to be almost consistent with the design column loads. The ratios of the loads carried by the piles in the tributary areas at 26 months after the E.O.C. were 0.84 (=44.0/66.4) to the design load and 0.66 (=44.0/52.5) to the measured total load.

The measured axial loads of the piles were less than a long-term allowable design load of the piles of 34.2 MN, and the measured stress of the DMWs were considerably less than the long-term allowable design stress of the soil-cement of 667 kPa. The ratios of the loads carried by the DMWs and the soil in the tributary areas at 26 months after the E.O.C. were 0.097 and 0.066 respectively to the measured total load. Consequently, it is confirmed that the DMWs used in a piled raft work effectively to support a part of vertical load in liquefiable and soft ground.

6 CONCLUSION

We carried out field monitoring of a piled raft foundation with grid-form cement deep mixing walls supporting an intermediate-isolated RC-frame high-rise residential building. As a result, it was found that the foundation settlement was 12 mm, and the ratio of the load carried by the piles was estimated to be 84% to the measured total load, 66% to the designed column loads at 26 months after the end of the construction. The grid-form cement deep mixing walls carried 9.7% of the total load. The DMWs played the role not only of coping with liquefiable sand but also of carrying partial

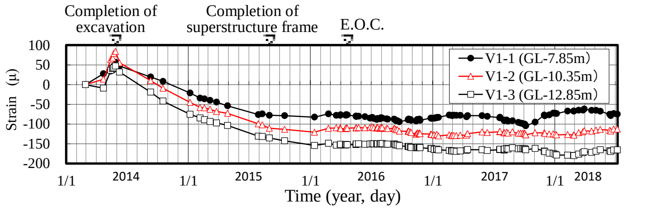


Fig. 5. Measured strain on soil cement walls.

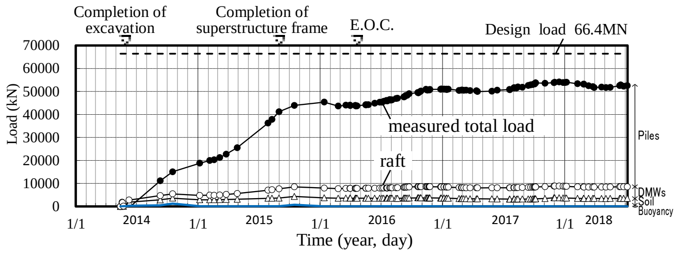


Fig. 6. Load sharing between raft and piles in the tributary areas vs. time.

load of the building and thus reducing the settlement of the soft cohesive stratum below the raft.

REFERENCES

Hamada, J., Tsuchiya, T., Tanikawa, T., Yamashita, K. (2015): Lateral loading tests on piled rafts and simplified method to evaluate sectional forces of piles, Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol. 46(2), 29-42.

Hamada, J., Yamashita, K. and Hirakawa, K. (2016): Case history of behavior of piled raft foundation supporting the tallest building in Japan constructed by top-down method, 19th Southeast Asian Geotechnical Conference & 2nd AGSSEA Conference (19SEAGC & 2AGSSEA).

Katzenbach, R., Arslan, U. and Moormann, C. (2000): Piled raft foundation projects in Germany, Design applications of raft foundations, Hemsley J.A. Editor, Thomas Telford, 323-392.

Poulos, H.G. (2001): Piled raft foundations: design and applications, Geotechnique 51(2), 95-113.

Poulos, H. G. and Bunce, G. (2008). Foundation design for the Burj Dubai – The world's tallest building-, Proc. of 6th Int. Conf. on case histories in Geotechnical Engineering, Paper No. 1. 47.

Taya, Y., Uchida, A., Yoshizawa, M., Onimaru, S., Yamashita, K. and Tsukuni, S. (2008): Simple method for determining lattice intervals in grid-form ground improvement, Japanese Geotechnical Journal , Vol.3(3), 203-212 (in Japanese).

Yamashita, K., Yamada, T. and Hamada, J. (2011): Investigation of settlement and load shearing on piled rafts by monitoring full-scale structures, Soil and Foundations, Vol.51(3), 513-532.

Yamashita, K., Hamada, J., Onimaru, S. and Higashino, M. (2012): Seismic behavior of piled raft with ground improvement supporting a base-isolated building on soft ground in Tokyo, Soils & Foundations, Vol.52(5), 1000-1015.

Yamashita, K., Wakai, S. and Hamada, J. (2013): Large-scale piled raft with grid-form deep mixing walls on soft ground, Proc. of the 18th Int. Conf. on Soil Mechanics and Geotechnical Engineering, 2637-2640.

Yamashita K., Hamada J. and Tanikawa T. (2016): Static and seismic performance of friction piled raft combined with grid-form deep mixing walls in soft ground, Soils & Foundations, Vol.56(3), pp. 559-573.