17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Seismic observation of large-scale piled raft foundation with grid-form deep mixing walls supporting isolated office building

J. Hamada[(1)], S. Wakai[(2)], K. Yamashita[(3)]

[(1)] *Chief Researcher, Takenaka Research & Development Institute, hamada.junji@takenaka.co.jp*
[(2)] *Chief Researcher, Takenaka Research & Development Institute, wakai.shuuichi@takenaka.co.jp*
[(3)] *Executive Manager, Takenaka Research & Development Institute, yamashita.kiyoshi@takenaka.co.jp*

Abstract

Piled raft foundations are recognised as one of the most economical foundation systems for vertical load, so that the foundations are applies for lots of building for many countries. And it is important and necessary to develop more reliable seismic design methods for piled raft foundations, especially in highly active seismic areas such as Japan. However, only a few case histories exist on the monitoring of the soil-pile-structure interaction behavior during earthquakes.

The purpose of this study is to clarify the seismic performance of piled raft foundations based on seismic observation records. The seismically monitored building is a large-scale twelve-story isolated office building founded on liquefiable sand underlain by soft cohesive soil in Tokyo, Japan. The grid-form deep mixing walls were employed in order to cope with the liquefiable sand and to reduce settlement of the foundation.

Accelerations of the building, dynamic sectional forces of the piles and dynamic earth pressures beneath the raft were observed during over 170 seismic events from April 25, 2012 to Aug. 4, 2019, including an earthquake with a magnitude of M8.1 on May 30, 2015. The maximum acceleration of 0.282 m/s^2 was observed on the 1st floor. The axial strain at the pile head (GL-8.5 m) was almost same with that at intermediate depth (GL-20 m) of the pile. That means a friction between the pile and around the soil enclosed by grid-form deep mixing walls was small. The bending strain, which is defined as a harf of differences of a couple of the strain attached at same section, at the pile head was considerably smaller than that at the intermediate depth. That means the bending moment at the pile head was reduced by enclosing with the grid-form deep mixing walls. When the ground was setteled downward, the incremental earth pressures between original ground and the raft were decreased and consequently, the incremental compression on the piles were increased.

Keywords: piled raft foundation; seismic observation; isolated building

1. Introduction

Piled raft foundations are recognised one of the most economical foundation systems for vertical load, that the foundation are applies for lots of building for many countries. It is important and necessary to develop more reliable seismic design methods for piled raft foundations, especially in highly active seismic areas such as Japan. Shaking table tests and static lateral loading tests using centrifuge model or large scale model and analytical studies have been carried out. Mendoza et al. (2000) reported on the static and seismic behaviour of a piled-box foundation supporting an urban bridge in Mexico City clay. The report examined the response of the soil-foundation system that was recorded during two seismic events in 1997 in which the foundation's maximum horizontal acceleration was 0.31 m/s^2. Yamashita et al. (2012) and Hamada et al. (2012) had successfully recorded seismic response of piled raft foundation with grid-form deep mixing walls (DMWs) supporting a base-isolated building during the 2011 off the Pacific coast of Tohoku Earthquake. These papers show the measured axial force and bending moment of the piles, earth pressure and pore-water pressure beneath the raft, and accelerations of the ground and the structure during the earthquake in which peak ground surface acceleration was 1.75 m/s^2. The results show a decrease in the input motion, which was reduced by the ground improvement, and an increase in bending moments due to horizontal ground deformation. Yamashita et al. (2015) had also showed static and seismic observation records of a friction piled raft with DMWs supporting a seven-story building at the same event. Although small changes in the foundation settlement and the load sharing between the raft and the piles were observed after the earthquake, it was confirmed that the friction piled raft showed a good performance in the soft ground. Hamada et al. (2014, 2015) reported static and seismic observation records on a piled raft foundation subjected to unsymmetrical earth pressure. Hamada et al. (2019) focuses on two seismic observation records during near and far earthquakes from the monitored building. Comparing to two deferent type events, sectional forces on piles due to input acceleration are discussed. The bending moments on piles were closely related to the horizontal acceleration of the building. However, the relationship was different depending on seismic type, the bending moments due to far earthquake were larger than those due to near earthquake.

However, not so many case histories exist on the monitoring of the soil-pile-structure interaction behavior during earthquakes. The purpose of this study is to clarify the seismic performance of piled raft foundations based on seismic observation records. This paper shows long-term monitoring records and seismic records of the piled raft foundation with DMWs supporting a large-scale twelve-story isolated office building. The monitored building is founded on liquefiable sand underlain by soft cohesive soil in Tokyo, Japan. Relationship between acceleration on the building and strain on the targeted piles were examined based on the monitored data.

2. Monitored building and soil conditions

Figure 1 illustrates a schematic view of the structure and foundation with a soil profile. The 12-story office building, 55.7 m in height above the ground surface and measuring 120 m by 100 m in plan, is a steel-framed structure with a base isolation system of laminated rubber bearings that was completed in 2011. The foundation levels were between depths of 3.6 and 7.2 m. The average contact pressure over the raft was 187 kPa. Thus, the piled raft consisted of 180 PHC (pretensioned spun high strength concrete) piles of 0.6 to 1.2 m in diameter where nominal compressive strength of concrete was 105 N/mm^2. The pile toes were embedded in the thick very dense sand layers below a depth of 44 m. The pile was constructed by inserting the precast piles into a pre-augered borehole filled with mixed-in-place soil cement for shaft and with concrete for foot protection in order to enhance the toe resistance. Figure 2 illustrates the foundation plan with the locations of the monitoring devices. The center-to center spacing of the piles was relatively large, 8-12 times the diameter in the tributary area.

The subsoil consists of an alluvial stratum to a depth of 44 m below the ground surface, underlain by a pleistocen very dense sand. The ground water table appears approximately 3 m below the ground surface. The soil profile down to a depth of 15 m is made of fill which consists of loose clayey sand, sandy clay and

© The 17th World Conference on Earthquake Engineering

rubble. Between the depths of 15 to 44 m, there lie very soft to medium silty clay which is slightly overconsolidated with an OCR of 1.3 or higher. The shear wave velocities derived from a P-S logging were 150 m/s at the foundation levels and 290 m/s in the dense sand below the depth of 44 m.

More details such as foundation design and ground improvement technique were given in previous papers (Yamashita et al., 2013, 2017).

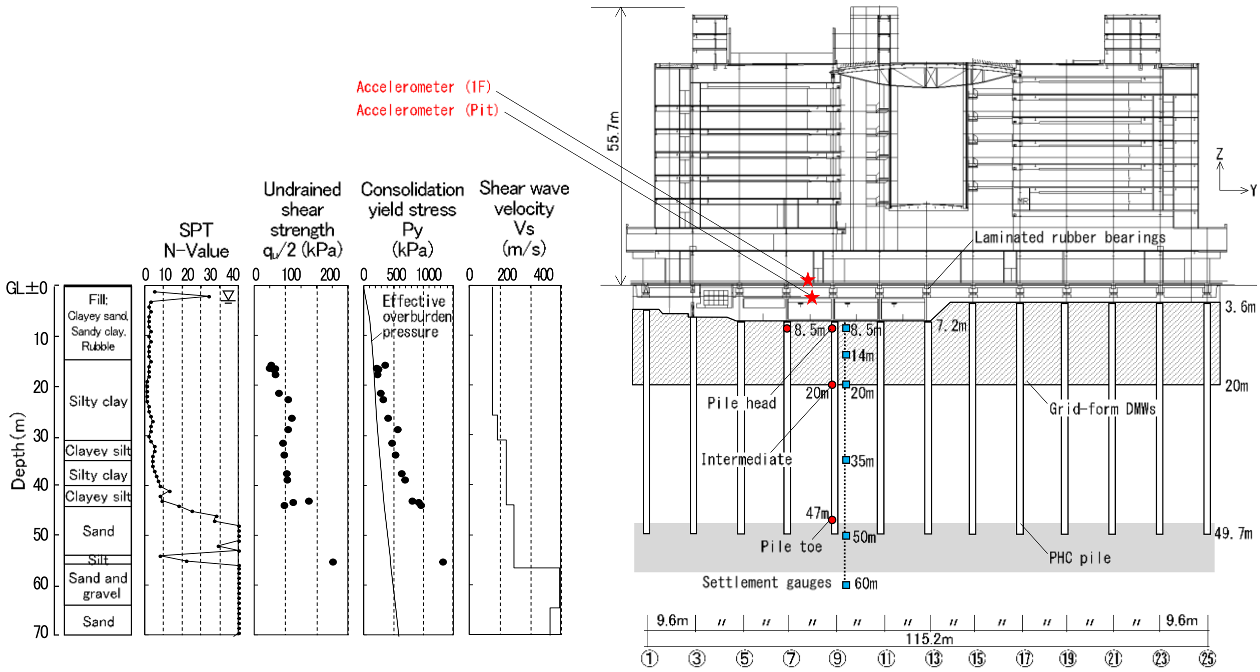
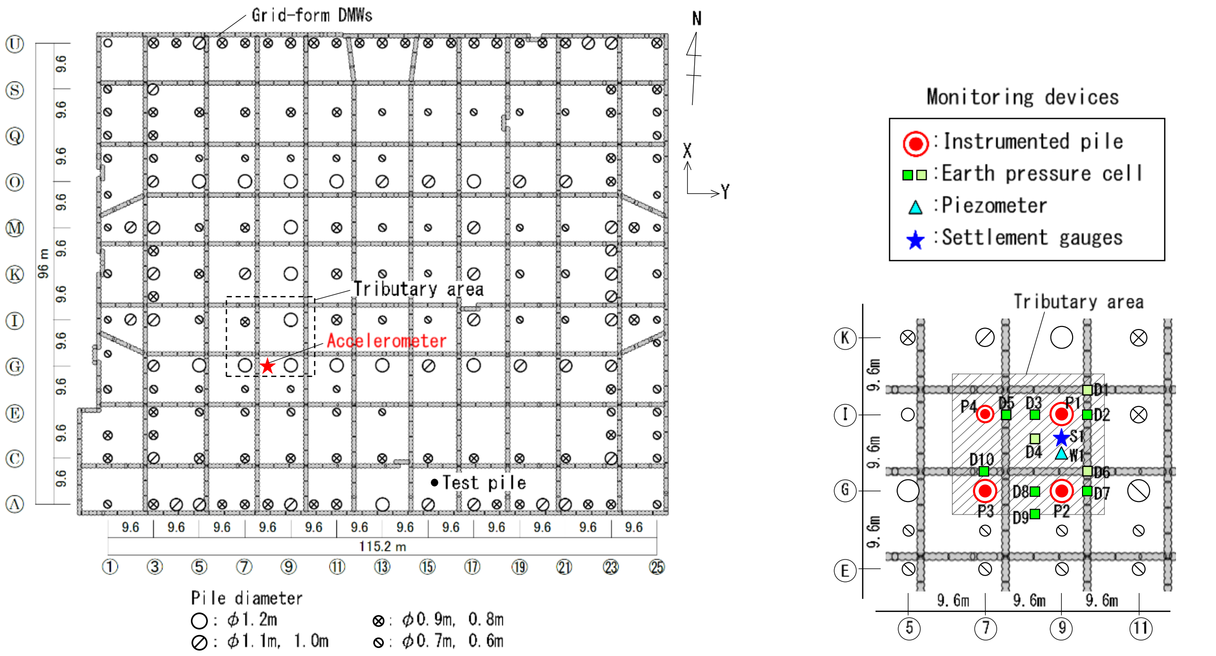


Fig. 1 – Schematic view of 12-story building and foundation with soil profile



(a) Layout of piles and grid-form cement deep mixing walls (b) Locations of monitoring devices

Fig. 2 – Foundation plan with locations of monitoring devices

3. Instrumentation

The locations of the monitoring devices are shown in Figs. 1 and 2. Four piles, P1, P2, P3 and P4, were provided with a couple of LVDT-type strain gauges at depths of 8.5 m (near pile head). In addition, P1 was also provided them at depth of 20.0 m (depth of DMWs toe) and 47.0 m (near pile toe) from the ground surface. In the tributary area of the instrumented piles, ten earth pressure cells and one piezometer were installed beneath the raft at the depth of 7.2 m. Earth pressure cells D3, D8, D9 were installed on the intact soil and earth pressure cells D2, D5, D7, D10 were installed on the deep mixing walls. Unfortunately, other three earth pressure cells (D1, D4 and D6) didn't work well. The vertical ground displacements below the raft were measured by differential settlement gauges. LVDT-type transducers were installed beneath the raft at depths of 8.5 m, 14.0 m, 20.0 m, 35.0 m and 50.0 m to measure the relative displacements to a reference point at a depth of 60.0 m. The measurement of the vertical ground displacements was begun during the excavation for the foundation construction. The measurement of the axial loads of the piles, the contact pressures and the pore-water pressure beneath the raft was begun just before the casting of the 0.6-m thick foundation slab.

As for the seismic observation, the NS, EW and UD accelerations of the building on the basement floor (Pit) and the first floor were recorded by triaxial servo accelerometers. The horizontal components of the triaxial accelerometer were oriented as shown in Figure 2. In this paper, the N-S direction and the E-W direction of the building are called X-direction and Y-direction, respectively. The axial forces and the bending moments of four piles, the vertical differential ground displacements, the contact earth pressures between the raft and the soil as well as the pore-water pressure beneath the raft were also measured during earthquakes in common starting time with the accelerometer at the Pit. The triggering acceleration is 0.004 m/s^2 on the Pit and the sampling rate is employed at 100 Hz. Minimum available values of acceleration, strain and earth pressure are 2.4×10^{-6} m/s^2 , $1.0\times10^{-4}\mu$ and 5.0×10^{-6} kPa, respectively. Measuring system is consisted of IC Card Data Logger and Dynamic Amplifier as shown in Table 1.

Table 1 Editorial Instructions

Device	Property
IC Card Data Logger	AD converter 24bit, Sampling 100Hz
Servo Accelerometer	Tri-axis, Full scale:±2000gal
Dynamic Amplifier	LVDT. Frequency Response:20Hz
Strain gauge	LVDT
Earth pressure cell	LVDT, Capacity:100, 200kPa
Piezometer	LVDT, Capacity:200kPa

4. Results of long-term measurements

Field monitoring was performed from the beginning of the construction to eight years after the end of the construction (E.O.C.). Figure 3 shows the measured vertical ground displacements below the raft versus time. The ground displacement at a depth of 8.5 m after the casting of raft was approximately equal to the settlement of the raft (red color), and refers to raft settlement in this paper. The differential settelement at 50 m and 35 m could not be measured after March, 2017, so the dashed lines are conjectured to be stable. At the time of the 2011 Tohoku earthquake, nine months before E.O.C., no significant change in raft settlement was observed after the event. Thereafter, the settlement reached 21 mm at about harf year after the E.O.C. and became stable after that.

Figure 4 shows the development of the measured axial loads of four piles (P1-P4) versus time. The axial loads became stable after E.O.C. in a same way as the raft settlement. Figure 5 shows the measured axial loads along Pile P1 versus time. The average shaft friction between the depths of 8.5 and 20.0 m was quite small, and about 80% of the pile head load was carried by the shaft friction after E.O.C. Figure 6 shows

© The 17th World Conference on Earthquake Engineering

the development of the measured contact pressure between the raft and the soil and that between the raft and the DMWs, together with the porewater pressure beneath the raft. The contact earth pressures on the DMWs were slightly increasing with seasonal variation.

Figure 7 shows the time-dependent load sharing among the piles, the soil, the DMWs and the buoyancy in the tributary area of the instrumented piles. After E.O.C., the load sharing among the piles, the DMWs and the soil was quite stable. The ratios of the load carried by the piles to the net load (the gross structure load minus the buoyancy) were estimated to be 0.64-0.71 after E.O.C., while the ratio of the net load carried by the soil to the net structure load and that carried by the DMWs were 0.14-0.16 and 0.15-0.2, respectively.

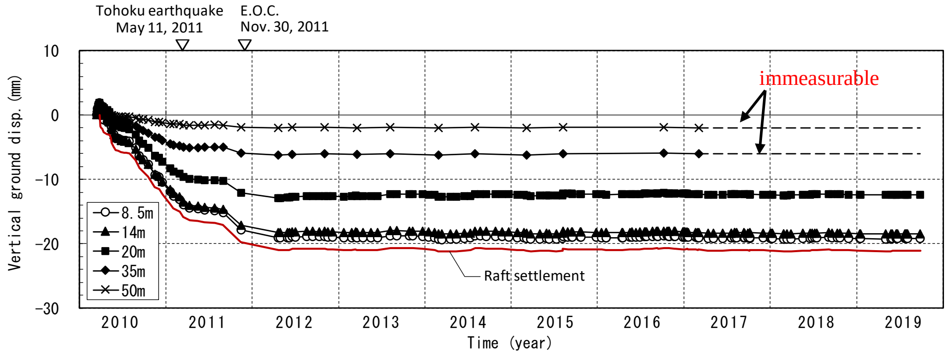


Fig. 3 – Time dependent vertical ground displacements below raft

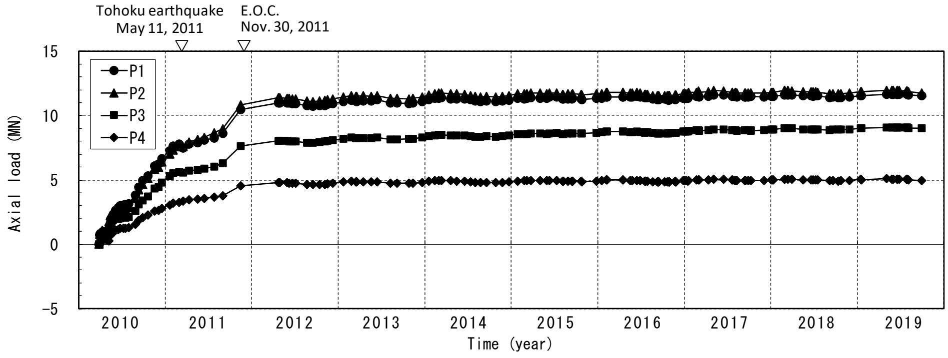


Fig. 4 – Time dependent pile head axial loads

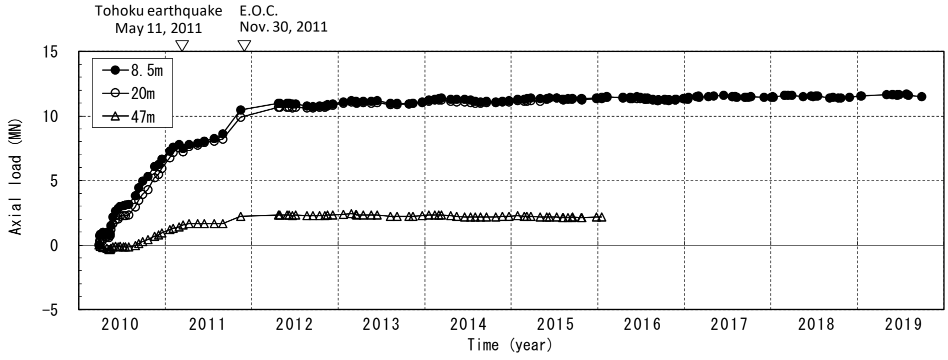


Fig. 5 – Time dependent axial loads of pile P1

© The 17th World Conference on Earthquake Engineering

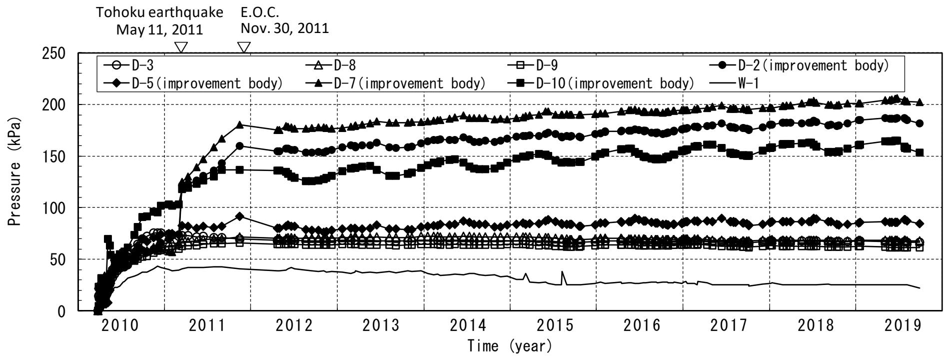


Fig. 6 – Time dependent contact earth pressure and porewater pressure

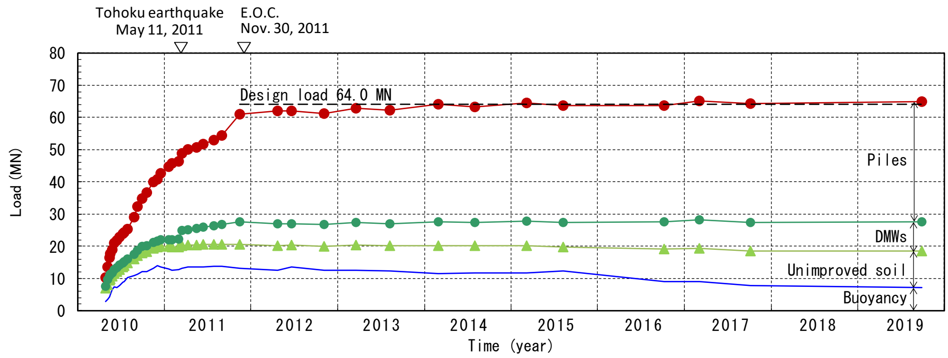
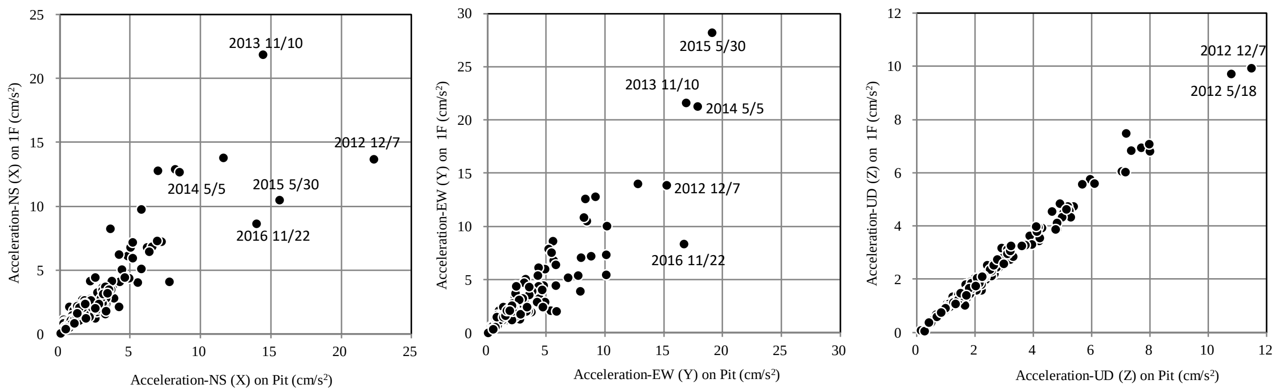


Fig. 7 – Time dependent load sharing among piles, DMWs and soil in the tributary area

5. Seismic response of piled raft foundation

5.1 Observed seismic events

Accelerations of the building, dynamic sectional forces of the piles, dynamic earth pressure beneath the raft, porewater pressure beneath the raft and vertical displacement of the ground were observed during over 170 seismic events from April 25, 2012 to Aug. 4, 2019, including an earthquake with a magnitude of M8.1. The maximum acceleration of 0.282 m/s^2 was observed on the 1st floor on May 30, 2015. Figure 8 shows observed peak accelerations of these seismic events.



(a) NS (X)-direction (b) EW (Y)-direction (c)UD (Z)-direction

Fig. 8 – Peak accelerations on pit and 1st floor of observed seismic events

© The 17th World Conference on Earthquake Engineering

Figure 9 shows locations of the monitored building and epicenters of relatively large seismic events. This paper focuses on the seismic event on May 30, 2015.

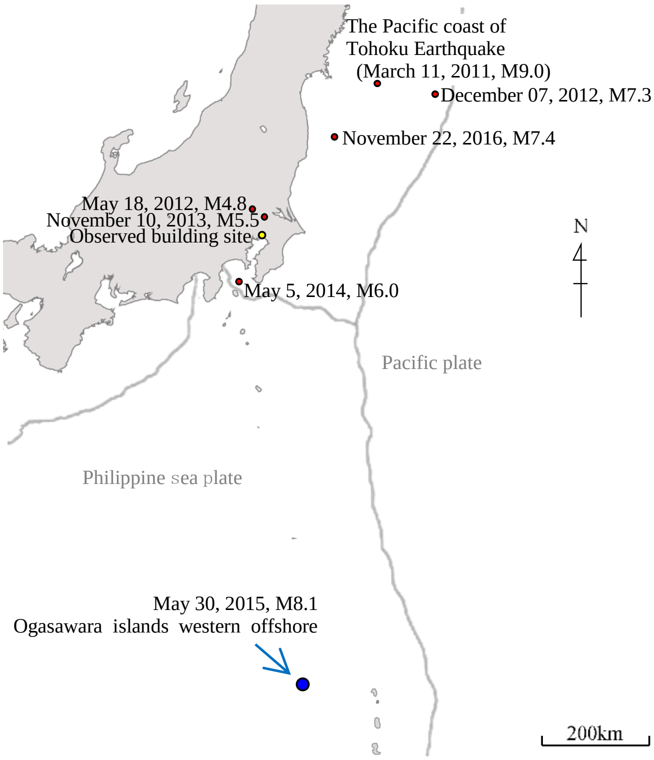


Fig. 9 – Locations of monitored building and epicenters of seismic events

5.2 Observed seismic responses of foundation

Figure 10 shows the time histories of the measured accelerations during the seismic event on May 30, 2015. A magnitude of the event is M8.1 and an epicenter of the event is Ogasawara ocean area, in which the maximum acceleration of 0.282 m/s^2 was recorded in EW (Y)-direction. Figure 11 shows the acceleration response spectrum of the observed accelerations. A natural period of the building is around 1.0 second without consideration of the isolaters effect.

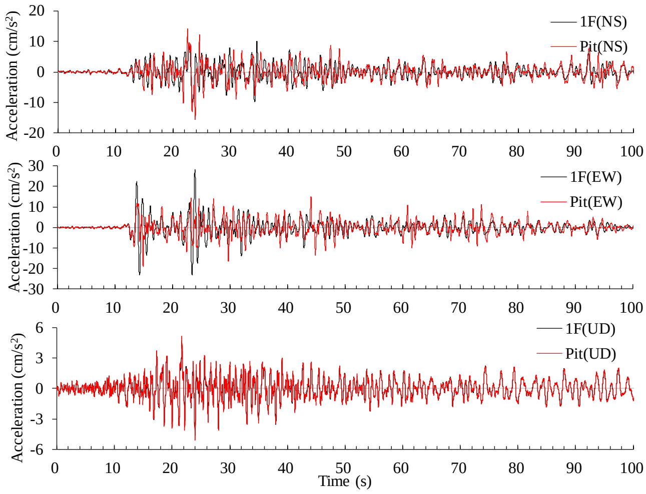


Fig. 10 – Time histories of measured accelerations

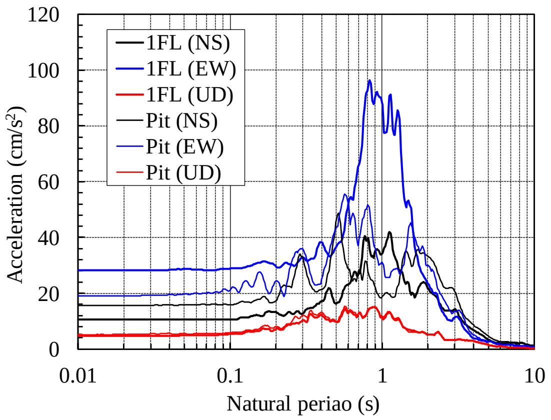


Fig. 11 – Acceleration response spectrum (h=5%)

© The 17th World Conference on Earthquake Engineering

Figure 12 shows the relationship between peak accelerations and incremental peak strains on the monitored piles during 179 events. The peak strains almost depend on peak accelerations. The strains at intermediate depth (P1-2E, P1-2W) are larger than those at pile head (P1-1E, P1-1W) or at pile toe (P1-3E). Figure 13 shows the relationship between peak accelerations and incremental peak contact pressures beneath the raft during the events. The peak pressures on DMWs (D2, D5, D7, D10) were almost larger than those on original ground (D3, D8, D9).

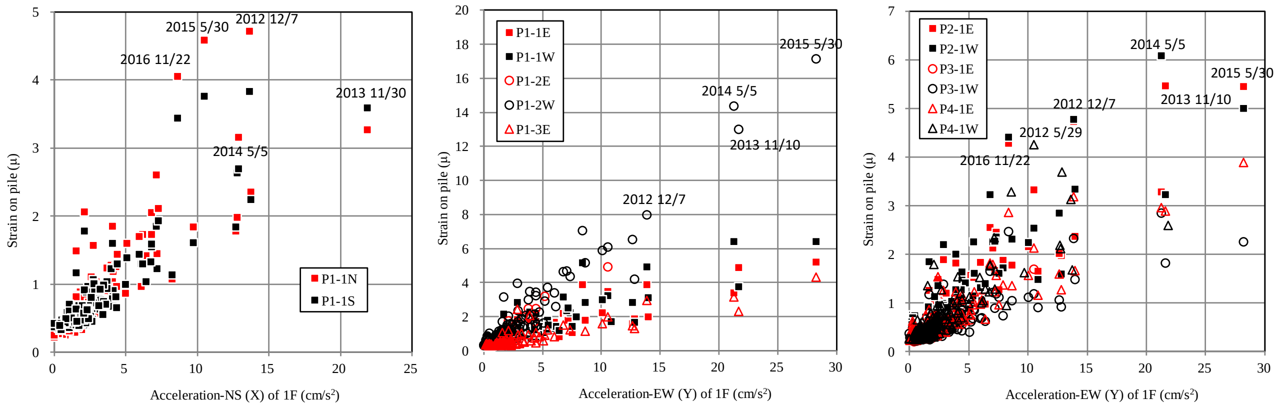


Fig. 12 – Peak strains on monitored piles

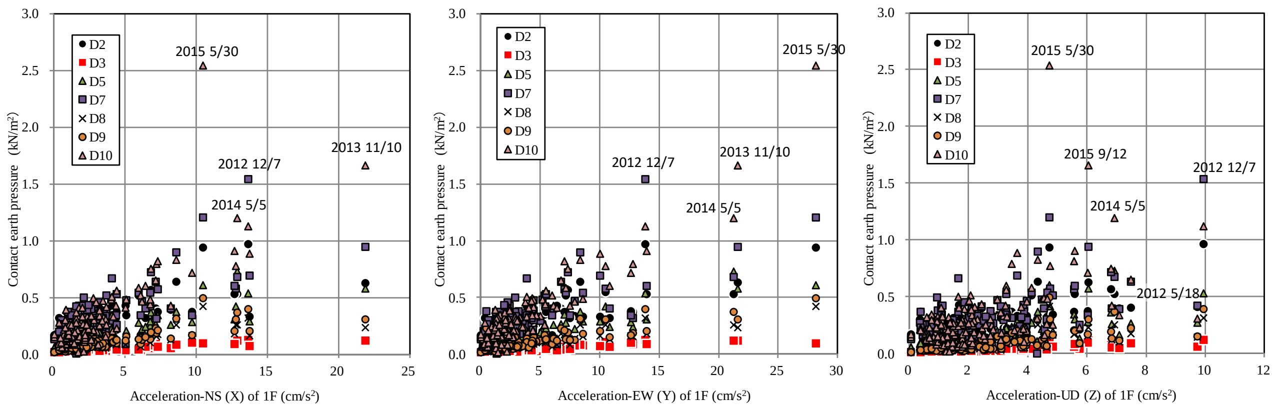


Fig. 13 – Peak contact pressures beneath the raft

Figure 14 shows the time histories of accelerations, vertical dispalcements of soil, sectional forces of the piles (axial strains and bending strains) and earth pressures amplified including the main shock during the Ogasawara event. The two dashed lines indicate the time when the inertial force of building in EW (X)-direction was maximum and minimum, i.e., time of 23.41 sec (time A) and 23.90 sec (time B) at Ogasawara event.

The vertical dispalcememts of soil, S1, S2 and S3 are differential settlemts between GL-8.5 m and 14 m, GL-14 m and 20 m, GL-20 m and 35 m, respectively. The positive vertical displacements are defined as rebound (strech of soil) .

The axial strain at the pile head (GL-8.5 m) was almost same with, or rather smaller than, that at intermediate depth (GL-20 m) of the pile. That means a friction between the pile and around the soil enclosed by grid-form deep mixing walls was small. When the incremental compression on the pile (negative axial strain means compression) occurred at a time C, the incremetal earth pressures of original ground beneath the raft (D3, D8, D9) were negative (,which means tension load) and also the incremental differential settlemets were negative (,which means settlement and shurink of soil). In addition, the

© The 17th World Conference on Earthquake Engineering

incremetal earth pressures of DMWs beneath the raft (D2, D5, D7, D10) was not correlated with those at original ground. These behaviours were complex, not only building was oscillating, but also ground was vertically oscillating. And the ground vertical oscillation was presumed to be large rather than the structure's oscillation.

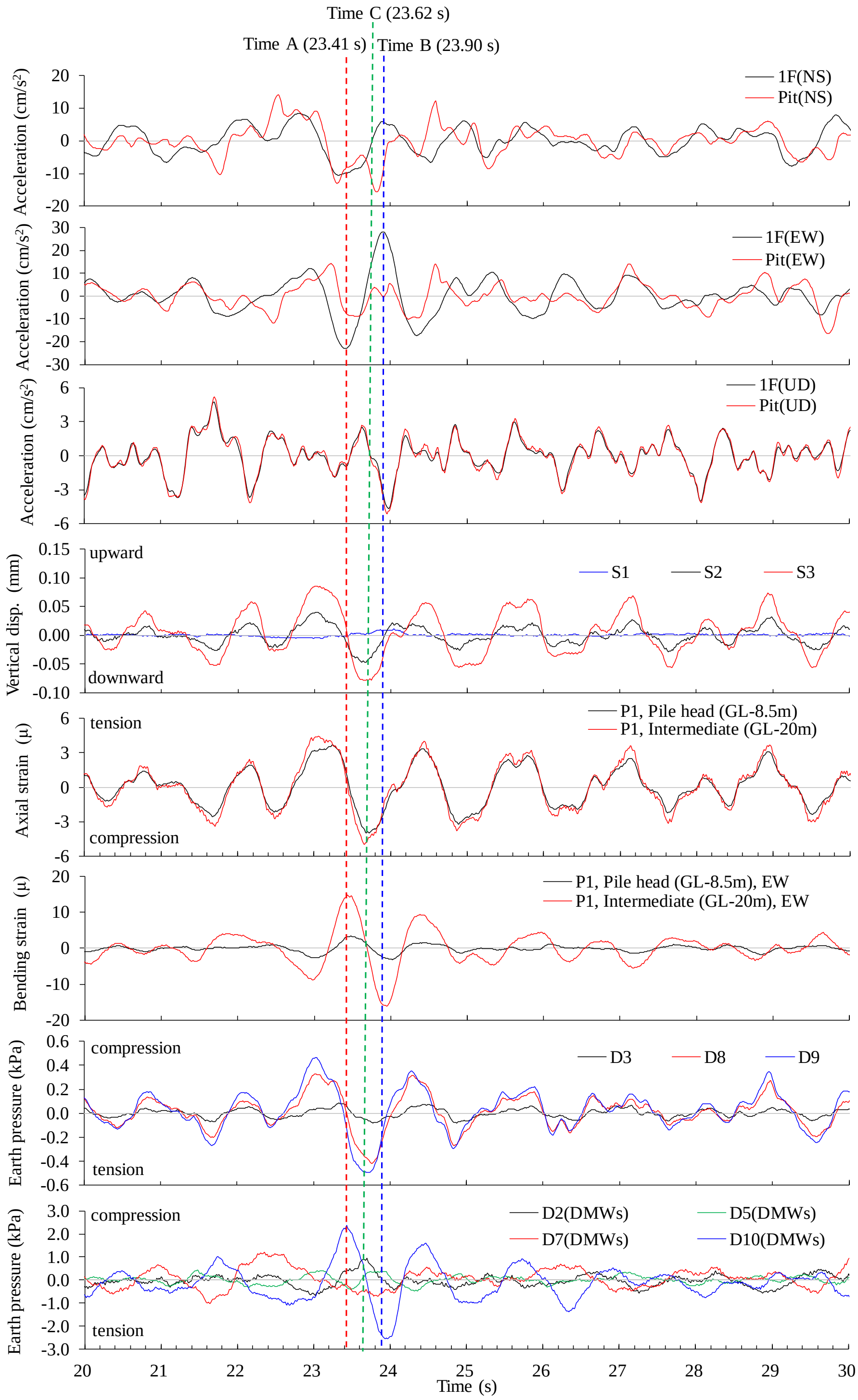
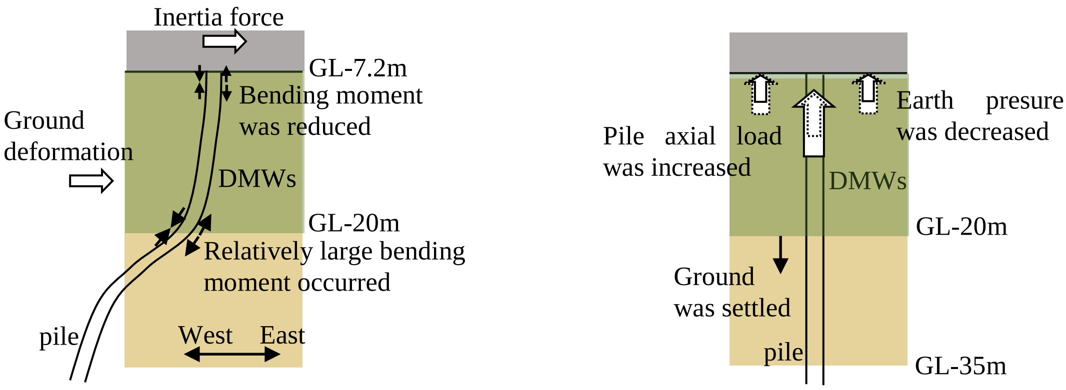


Fig. 14 – Time histories of accelerations, differential settlements, strains on piles and earth pressures during Ogasawara event (May 30, 2015)

© The 17th World Conference on Earthquake Engineering

The bending strain is defined as a harf of differences of a couple of the strain attached at same section, (strain at east side of pile – strain at west side of it)/2). The bending strains at the pile head (GL-8.5 m) were considerably smaller than those at the intermediate depth (GL-20 m, depth of DMWs toe). That means the bending moments at the pile head were reduced by enclosing with the grid-form deep mixing walls, whereas those at the intermediate depth were enlarged by gap of ground deformation due to DMWs.

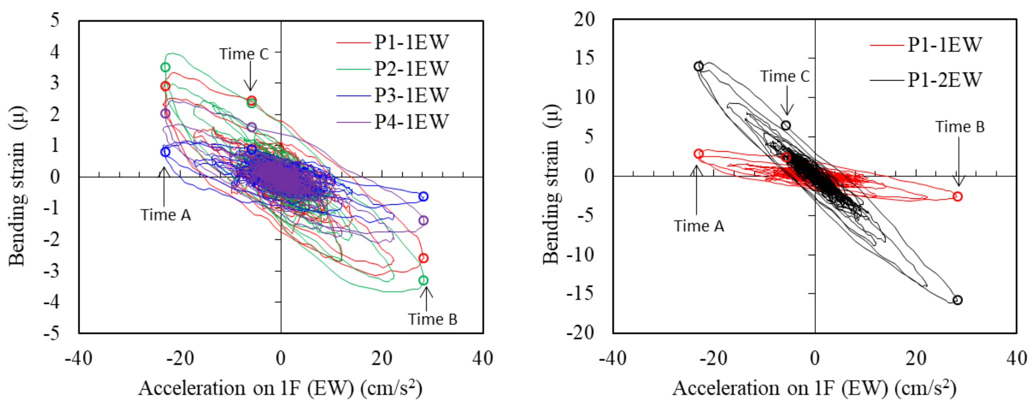
Shematic images at time A and time C are shown in Figure 15 (a) and (b), respectively. At time A, the inetia force of the building was maximum to East direction, so the building deformed to East direction (positive Y-direction). And the DMWs and innner ground enclosed by them were supposed to be moving in the same direction. And the bending moments at pile head and intermediate depth are positive. At time C, the ground was setteled downward. Consequently, the incremental earth pressures between original ground and the raft were decreased and the incremental piles' axial loads were increased.



(a)Time A (at maximum inertial force of structure) (b) Time C (at maximum incremental axial load of pile)

Fig. 15 – Schematic image at Time A and C

Figure 16 shows the relationship between the horizontal acceleration on 1st floor in EW (Y)-direction and the bending moments of Piles P1, P2, P3 and P4 at the pile head and P1 at the intermediate depth. Bending strains (bending moments) were generally caused by inertial force of superstructure and ground deformation. The observed bending strains were closely related to the acceleration on the 1st floor (, which is correspond to inertial force of the building). And the bending strain at intermediate depth of pile P1 (P1-2EW) were considerably larger than those at pile head of same pile (P1-1EW) as shown in Fig.14.



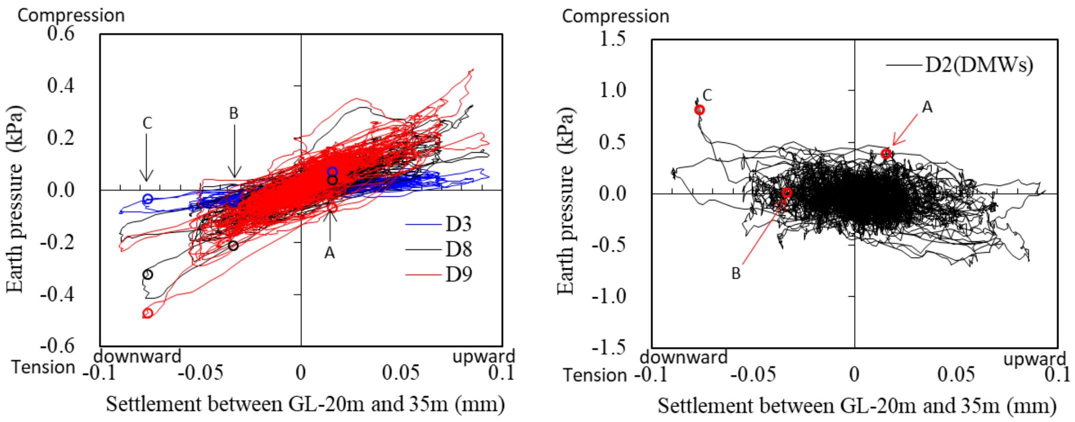
(a) Difference of piles (b) Difference on pile head and intermediate depth

Fig. 16 – Bending strains on piles versus acceleration on 1st floor

© The 17th World Conference on Earthquake Engineering

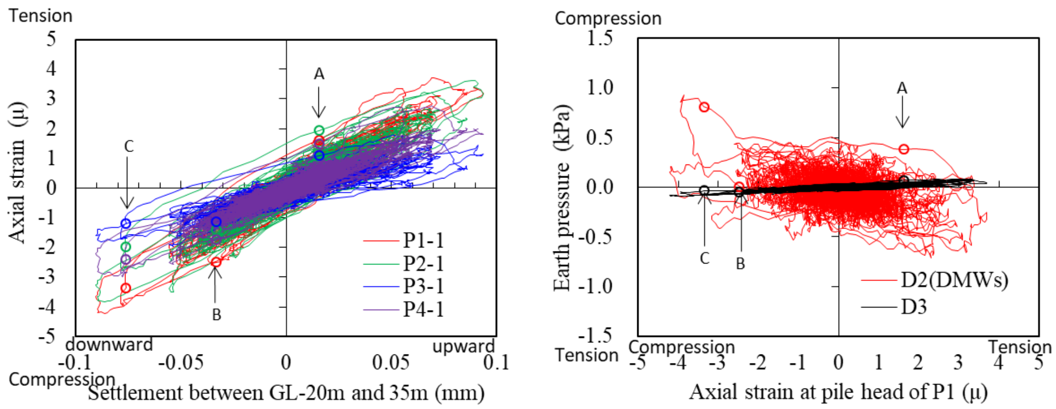
Figure 17(a) shows the differential settment between GL-20 m and 35 m versus contact earth pressure of original ground beneath the raft. As shown in Fig.14, the earth pressures were closely correlated with the differential settlemenent. Figure 17 (b) shows the differential settment between GL-20 m and 35 m versus contact earth pressure of DMWs beneath the raft. The earth pressures were slightly correlated with the differential settlemenent, however the relation was innvers as those at original ground.

Figure 18(a) shows the differential settlement between GL-20 m and 35 m versus axial strains on the pile heads. The incremental compression on the piles were caused by the groud settlement (moving downward of the ground). Figure 18(b) shows earth pressures on original ground and DMWs versus axial strains on the pile head at P1. The contact earth pressure on the original ground behaved closely related with axial strain on the pile, whereas the contact pressure on the DMWs behaved on the contrary to that on the original ground.



(a) Original ground pressure (b) DMWs pressure

Fig. 17 – Settlements versus earth pressures



(a) Axial strain versus settlement (b) Earth pressure versus axial strain

Fig. 18 – Relationship among axial strain, earth pressures and settlement

6. Conclusions

Seismic observations on the piled raft foundation with grid-form deep mixing walls supporting large isolated building were performed over seven years. Based on the seismic records, it was found as follows;

© The 17th World Conference on Earthquake Engineering

The bending moments on piles were closely related to the horizontal acceleration of the building during small earthqake as without action of the base-isolatation system. The bending moments at the pile heads were reduced by enclosing with the grid-form deep mixing walls. The value were considerably smaller than that at the intermediate depth.

The axial strain at the pile head was almost same with that at intermediate depth of the pile because friction between the pile and around the soil enclosed by grid-form deep mixing walls was small.

The earth pressures on original ground were closely correlated with the ground settlemenent. On the other hand, those on the DMWs seem to have no correlation or rather negative correlation with the ground settlement. When the ground was setteled downward, the incremental earth pressures between original ground and the raft were decreased and consequently, the incremental compression on the piles were increased.

7. Acknowledgements

The authors are grateful to Messrs. H. Matsuzaki, H. Nagaoka of Takenaka Corporation and Mr. N. Nakayama (formerly of Takenaka Corporation) for their contribution to the foundation design.

8. References

[1] Mendoza, M. J., Romo, M.P., Orozco, M. and Dominguez, L. (2000): Static and seismic behavior of a friction pile-box foundation in Mexico City clay. *Soils & Foundations*, Vol.40, No.4, 143-154.

[2] 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, Special Issue on Geotechnical Aspects of the 2011 off the Pacific Coast of Tohoku Earthquake*, Vol.52, No.5, 1000-1015.

[3] Hamada, J., T., Tanikawa, T., Onimaru, S. and Yamashita, K. (2012a): Seismic observations on piled raft foundation with ground improvement supporting a base-isolated building. *15thWCEE*.

[4] Yamashita, K., Hamada, J. and Tanikawa, T. (2015): Performance of friction piled raft with deep mixing walls in soft ground during the 2011 East Japan earthquake. *6ICEGE*.

[5] Hamada, J., Aso, N., Hanai, A. and Yamashita, K. (2014): Seismic observation on piled raft foundation subjected to unsymmetrical earth pressure. *TAKENAKA Technical report* No.70, p10.

[6] Hamada, J., Aso, N., Hanai, A. and Yamashita, K. (2015): Seismic performance of piled raft subjected to unsymmetrical earth pressure based on seismic observation records. *6ICEGE*.

[7] Hamada, J. and Yamashita, K. (2019): Seismic observations on piled raft foundation subjected to unsymmetrical earth pressure during far earthquake and near earthquake. *Geotechnical Engineering Journal of the SEAGS & AGSSEA* Vol. 50 No. 4, 5-14.

[8] Yamashita, K., Wakai, S. and Hamada, J.: Large-scale Piled Raft with Grid-Form Deep Mixing Walls on Soft Ground, Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013

[9] Yamashita, K., Wakai, S, Hamada, J. and Tanikawa, T.: Pile group interaction based on field monitoring and load tests, Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol.48, No.3, pp.47-57, 2017, 9.

© The 17th World Conference on Earthquake Engineering