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Special Contribution

Piled Raft Foundation Combined with Deep Mixing Wall Grid

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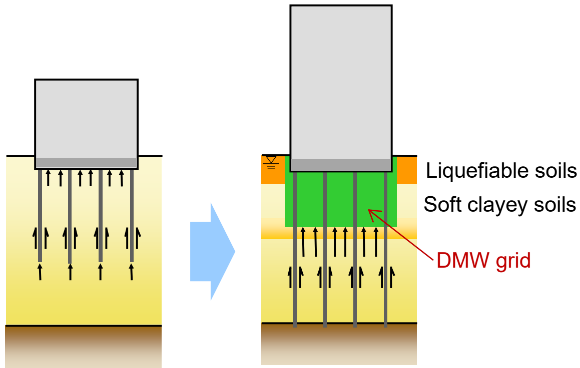
Abstract. An advanced piled raft system, which can be used in very soft clayey soils and/or liquefiable soils, called “piled raft foundation combined with deep mixing wall grid” has been developped. The piled raft system was employed for a 12-story building and field monitoring of the soil-structure system was performed. During the monitoring period, the 2011 Tohoku Earthquake (M9.0) struck the site (about 380 km from the epicenter). In this paper, the static and dynamic monitoring results of the advanced piled raft system, and a numerical simulation using a 3-dimentional finite element (FE) model to examine the performance under strong earthquakes were presented.

1. Introduction

In recent years, piled raft foundation, which means a piled foundation combining piles and raft response in a design, has been used in many countries. In Japan, since a basic design framework for piled rafts was established in the early 2000s, piled rafts have been employed for lots of buildings including high-rise buildings over 200 m in height. At the same time, field evidence, especially the settlement and the load sharing between piles and raft, was accumulated by monitoring full-scale structures, and the effectiveness of piled rafts in reducing average and differential settlements has been confirmed (Yamashita et al., 2011a).

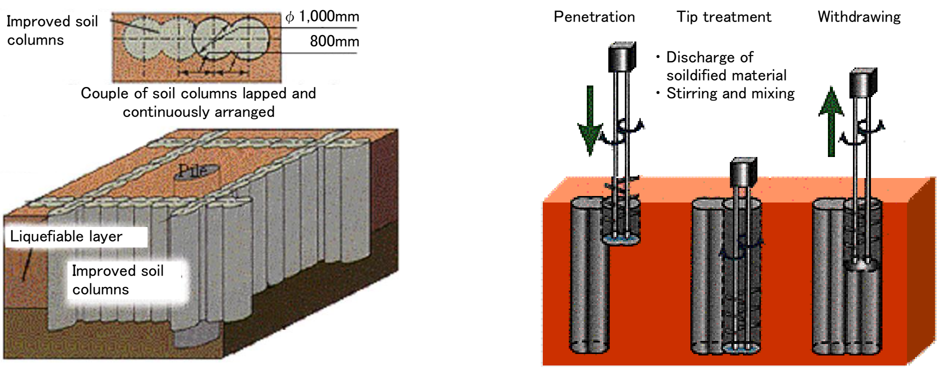
2. Piled raft combined with ground improvement

The most effective application of piled rafts occurs when the raft can provide adequate load capacity but the settlement and/or differential settlements of the raft alone exceed the allowable values, hence favorable situations may be soil profiles consisting of relatively stiff clays and relatively dense sands (Poulos, 2017). On the other hand, unfavorable situations are profiles with very soft clayey soils and/or requifiable soils near the surface of the raft, which may be subjected to consolidation settlement and/or seismic liquefaction. To cope with this, an advanced piled raft system, i.e., a piled raft foundation combined with gound imprpvement, has been developed (Yamashita et al., 2011b).



(a) Piled raft foundation (b) Piled raft combined with DMW grid

Fig. 1. Advanced piled raft system



(a) Schematic of DMW grid (b) Construction procedure (2-axle type)

Fig. 2. Deep mixing wall (DMW) grid

Fig. 1 illustrates the advanced piled raft system called "piled raft combined with deep mixing wall (DMW) grid". The DMW grid (illusutrated in Fig. 2), which is expected to restrict the shear deformation of the soil within the grid, is used as a countermeasure of soil liquefaction under the raft as well as to increase the bearing capacity of the raft foundation. Moreover, the DMWs are expected to resist the inertial force from the structure during strong earthquakes.

3. Static and Dynamic Monitoring of 12-story Building on Soft Ground

Fig. 3 illustrates a schematic view of a 12-story residensial building and its foundation with a typical soil profile. The building located in Tokyo is a reinforced-concrete structure with a seismic base-isolation system. The total load in the structural design was 198.8 MN (average pressure over the raft was 200 kPa). The subsoil consists of very soft to medium clayey soil layers to a depth of 43 m, underlain by dense sandy layers. The groundwater table appears about 1.8 m below the ground surface, and it was ascertained that the silty sand near the ground surface had a potential for liquefaction with a peak ground acceleration (PGA) of 0.2g.

Hence, to prevent liquefaction of the silty sand as well as to provide adequate load capacity of the raft, a piled raft combined with DMW grid (which was extended to a depth of 16 m with the bottom being embedded in the stiffer silty clay) was employed. Sixteen PHC piles, whose toes reached the very dense sand-and-gravel layer, were used to reduce the settlement to acceptable levels. Fig. 4 illustrates the foundation plan with the layout of the piles and the DMW grid (area replacement ratio is 0.25). The effectiveness of the piled raft system was confirmed by comparing performance and cost with conventional large-diameter cast-in-place concrete pile foundation.

Field monitoring on the settlement and the load sharing between piles and raft was performed both statically and dynamically (Yamashita et al., 2012). The locations of the monitoring devices are shown in Fig. 4. Two piles, 5B and 7B, were provided with LVDT strain gauges. Fig. 5 shows the measured vertical ground displacement just below the raft after the casting of the raft. The vertical ground displacement might be approximately equal to settlement of the raft, and it refers as raft settlement here. Fig. 6 shows the time-dependent vertical load sharing among the piles, the DMWs, the soil and the buoyancy in the tributary area of columns 5B and 7B indicated in Fig. 4. During the monitoring period, on March 11, 2011, the 2011 Tohoku Earthquake (M=9.0, about 380 km from the epicenter) struck East Japan, and the seismic responses of the 12-story building were successfully recorded. The PGA recorded at the site was 0.18 g as shown in Fig. 7. Just before the earthquake, the raft settlement was 17.3 mm, and the ratio of the load carried by the piles to the net load (the gross load minus the buoyancy) was estimated to be 0.67 where the ratio of the net load carried by the DMWs to the net load was 0.26, fairly greater than that carried by the soil. After the earthquake on March 15, the raft settlement increased by only 0.3 mm to 17.6 mm, and thereafter, the raft settlements ranged from 17 to 18 mm. Furthermore, almost no change in load sharing among the piles, the DMWs and the soil was observed after the earthquake. Thus, both the raft settlement and the load sharing were quite stable after the earthquake.

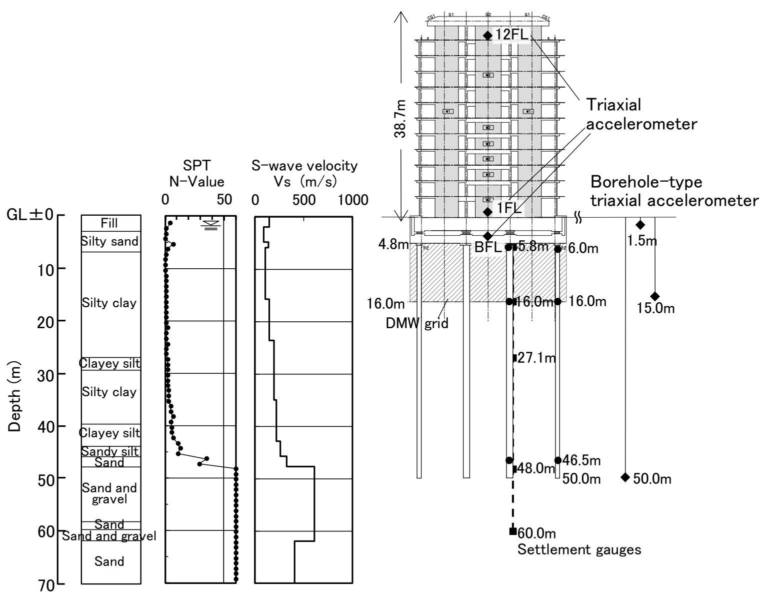


Fig. 3. Schematic of 12-story building and foundation with soil profile

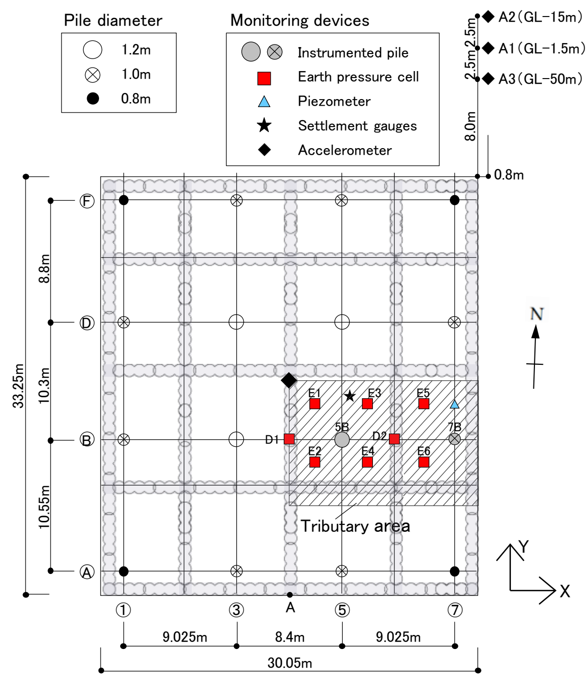


Fig. 4. Foundation plan with layout of piles and DMW grid

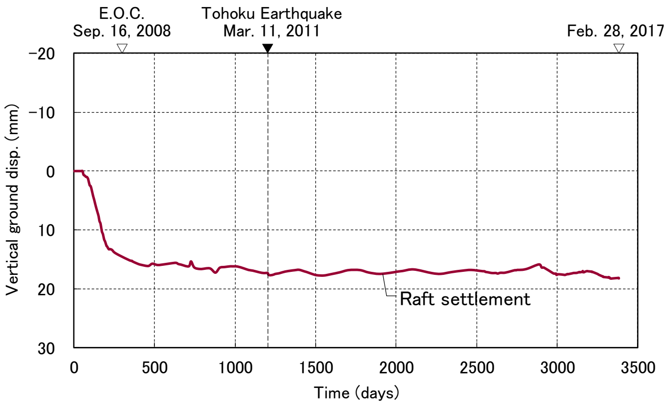


Fig. 5. Measured vertical ground displacements just below raft

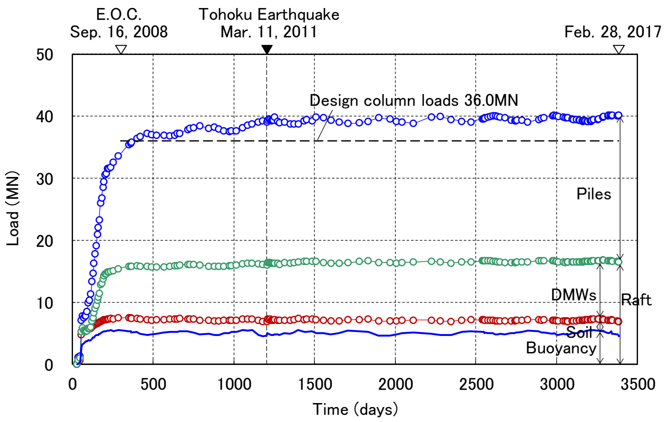


Fig. 6. Load sharing among piles, DMWs and soil in the tributary area

Fig. 7 shows the acceleration time histories recorded near the ground surface, on the raft and the 1st and 12th floors in the EW direction. The duration of the seismic motion was longer than 600 s. The peak acceleration on the 1st floor was significantly reduced compared to that on the raft, which indicates that the base-isolation system acted quite well. In addition, the peak acceleration on the raft was clearly reduced compared to that near the ground surface due to the input losses caused by the dynamic soil-structure interaction.

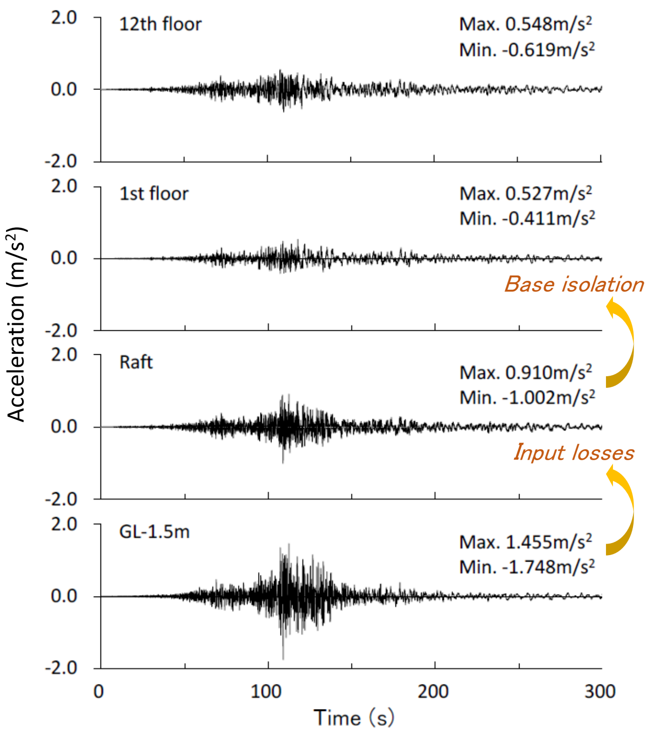


Fig. 7. Acceleration time histories recorded on the ground and structure (EW)

Fig. 8 shows the relationship between the axial force and the bending moment measured at the pile head of Pile 5B, which were obtained by combining the components in NS and EW directions. In order to check the performance of the piles, the design interaction curves of the SC pile (which was used for top portion) are also shown in Fig. 8. It was found that the increments in axial force were remarkably small due to the action of the base-isolation system, and that the measured bending moments were fairly small compared to the damage limit state values (the unit stress at the edge of the concrete is almost in the elastic condition).

4. Performance Under Strong Earthquakes through Numerical Simulation

To examine the seismic performance of the piled raft system under strong earthquakes, a numerical simulation was conducted using a nonlinear 3-dimentional FE model illustrated in Fig. 9 (Yamashita et al., 2018). As strong earthquake motions for the present analysis, input motion of Level 2 earthquake (with mean return period of approximately 500 years) was employed. Fig. 10 shows the code-defined acceleration response spectrum of the Level 2 motion on the engineering bedrock. Fig. 11 shows the acceleration time history of the input motion using Kobe phase data on the bedrock (2E). The input motion was applied horizontally in the NS direction at a depth of 75 m.

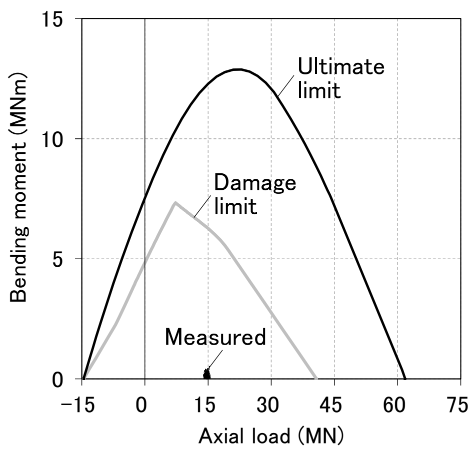


Fig. 8. Relation of axial force with bending moment (Pile 5B)

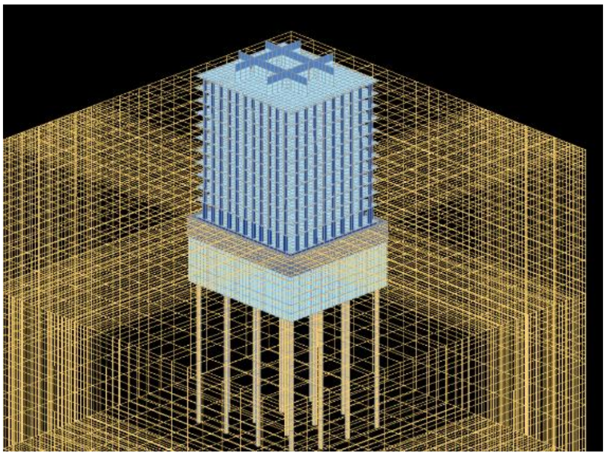


Fig. 9. 3-dimentional FE model

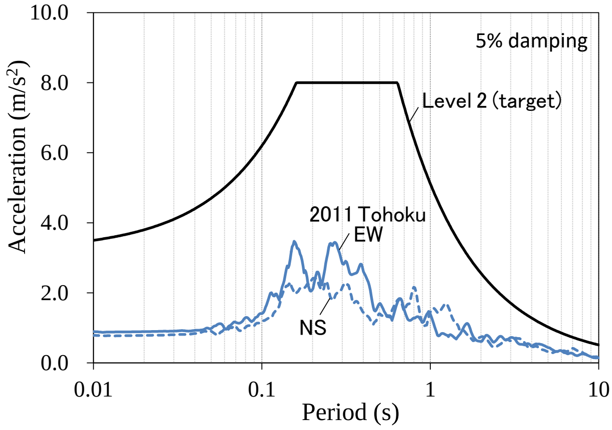


Fig. 10. Acceleration response spectra of Level 2 motions and 2011 Tohoku Earthquake on bedrock

To verify the deformation parameters of the DMWs and the soil and to validate the simulation method, a numerical simulation was carried out using the moderate earthquake motion recorded during the 2011 Tohoku Earthquake. The response spectra of the input accelerations on the bedrock (which was derived from the records at a depth of 50 m) is shown in Fig. 10. The peak horizontal displacement profiles of the ground and superstructure at the center and the peak bending moment profiles of Pile 5B are shown in Fig. 12, compared with the observed values. The displacements are relative ones to the reference point at a depth of 50 m. It is seen that the simulated values of ground and structure response and those of pile bending moment agree well with the observed ones, and that the dynamic 3-dimentional FE simulation method is capable of reproducing the observation records and that the deformation parameters of the unimproved and the stabilized soils at relatively small strains were appropriate.

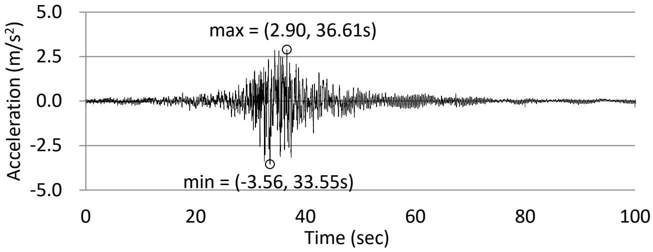
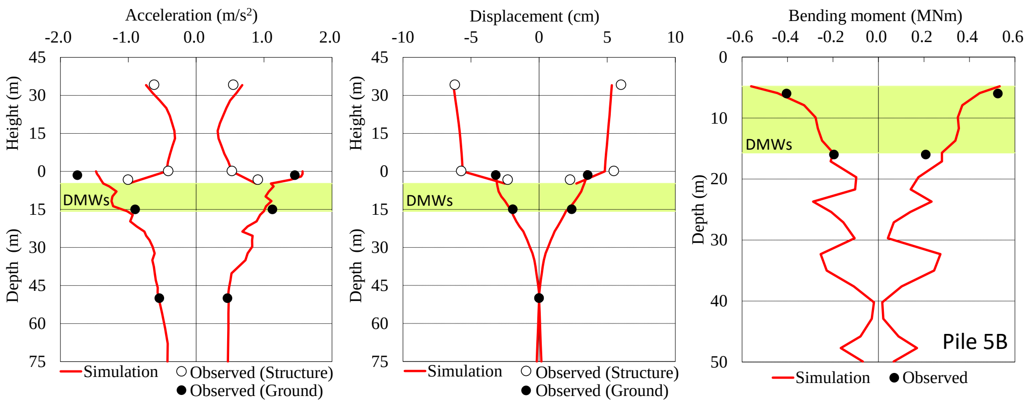


Fig. 11. Input acceleration time history (Kobe phase)

Then, the seismic response analyses under Level 2 earthquakes were conducted, where numerical cases without the DMWs were also conducted. Fig. 13 shows the peak bending moment profiles of Pile 5B. The bending moment near the pile head in the case with DMWs was significantly small in comparison with that in the case without DMWs. To clarify the difference in pile bending moment in the cases with and without DMWs, the ground deformation and the shear force acting at the pile head during the shaking were examined.



(a) Acceleration (b) Displacement (c) Bending moment

Fig. 12. Profiles of peak response of ground and structure and pile bending moment (EW)

Fig. 14 shows the profiles of the peak horizontal displacement of the DMWs and ground under the mid-side of the raft. It is seen that the displacements near the raft bottom of the DMWs were markedly smaller than those of the ground in the case without DMWs. Fig. 15 illustrates the equilibrium of lateral external forces and resistant forces at the raft bottom when the bending moment of Pile 5B was at its maximum. Regardless of the presence of the DMWs, the inertial forces of the superstructure were very small compared to the earth pressure on the raft side. This occurred because of the action of the base-isolation system. In the case with DMWs, the external forces were carried mostly by the DMWs and the load carried by the piles was much smaller than that in the case without DMWs. In addition, it is noted that the tensile failure of the DMW grid seemed to be limited to the bottom portion as illustrated in Fig. 16.

Thus, both the ground displacement near the raft bottom and the shear force acting at the pile head were decreased by the presence of the DMWs. As a result, the bending moments near the pile head were significantly smaller than those in the case without DMWs.

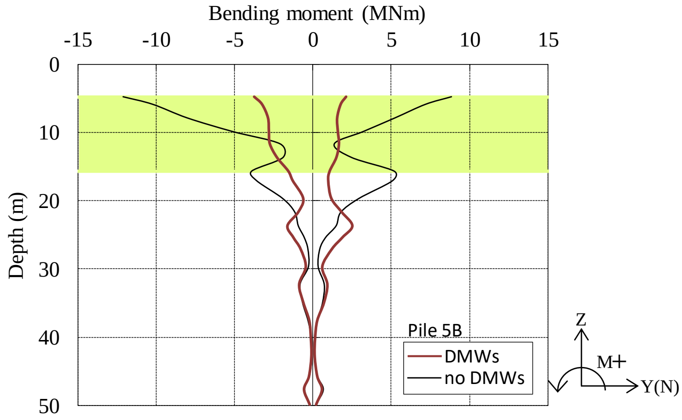


Fig. 13. Peak bending moment profiles (Pile 5B)

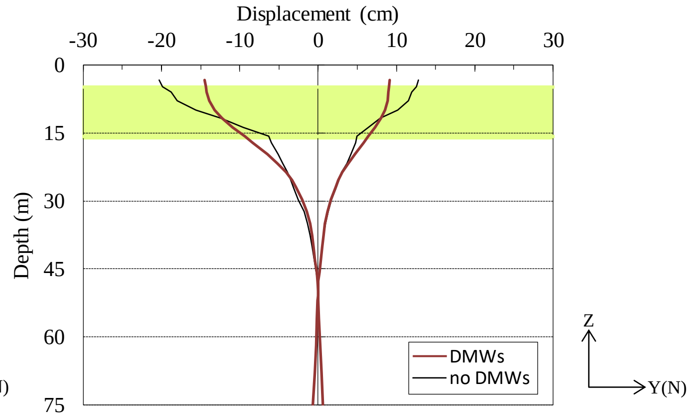


Fig. 14. Peak displacement profiles of DMWs and ground under the mid-side of raft

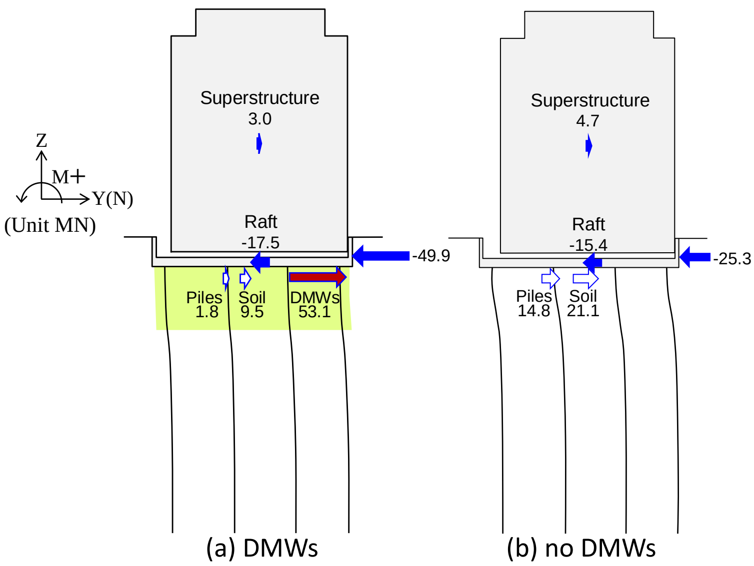


Fig. 15. Equilibrium of lateral forces at raft bottom when bending moment (Pile 5B) was at its maximum

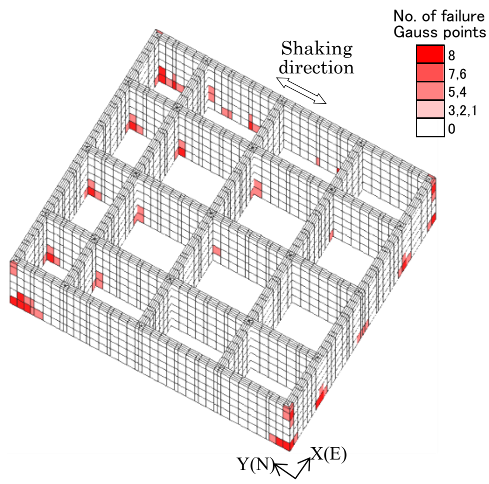


Fig. 16. Extent of tensile failure in DMW grid

5. Concluding Remarks

Based on the static and dynamic monitoring of the 12-story building, it was found that the piled raft combined with DMW grid showed a good performance under the moderate seismic motion as well as ordinary conditions. In addition, through the numerical simulation using a 3-dimentional FE model under strong earthquakes, the ground displacement near the raft bottom and the shear force acting at the pile head were found to be significantly decreased by the presence of the grid. This indicates that the DMW grid was quite effective in reducing the sectional force of the piles in the piled raft system.

The DMW grid could be designed more rationally by following the principles of a performance-based design. The reason is that the DMW grid can be regarded as supplementary structural elements in the foundation system, and minor damage to the grid can be tolerated under strong earthquakes, provided that the required foundation performance has been satisfied.

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A brief CV of Dr. Kiyoshi Yamashita

Dr. Yamashita obtained his Bachelor and Master of Engineering from Tokyo Institute of Technology. He joined Takenaka Corporation in 1977 as a research engineer. He was a deputy general manager in Takenaka R&D Institute from 2009 to 2012. His reserch interests are design and performance of piled raft foundations under both ordinary and seismic conditions. He engaged in foundation design of around 50 buildings in which piled rafts were employed. He also planned and executed long-term field monitoring of the selected piled rafts. He has published more than 150 technical papers including more than 20 journal articles and 40 conference papers. He received the JGS (Japanese Geotechnical Society) Awards in 1996, 2013 and 2018.