Seismic Observations on Piled Raft Foundation Subjected to Unsymmetrical Earth Pressure During Far Earthquake and Near Earthquake

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ABSTRACT: Seismic observations on piled raft foundation subjected to unsymmetrical earth pressure have been conducted just after the 2011 off the Pacific coast of Tohoku Earthquake. The seismically monitored building is a seven-story building with three basement floors, subjected to unsymmetrical earth pressure, located in Tokyo, Japan. Accelerations of the building, dynamic sectional forces of the piles and dynamic earth pressures on both sides of the embedded foundation and those beneath the raft were observed during over 550 seismic events including an earthquake with a magnitude of M8.1. The maximum acceleration of 0.358 m/s^2 was observed on the building foundation. Based on the seismic records, it was confirmed that a lateral inertial force of the building was transferred to the subsoil through the raft. Comparing to different seismic type, the bending moments on piles due to far earthquake having relatively long period were larger than those due to near earthquake. It was also found that the ratio of the lateral load carried by the piles to the lateral inertia force of the building was estimated to be about 10 to 30 %.

KEYWORDS: Piled raft foundation, Seismic observation, Unsymmetrical earth pressure

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. Recently, Yamashita et al. (2012) and Hamada et al. (2012) had successfully recorded seismic response of piled raft foundation 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.

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 static and seismic observation records on a piled raft foundation subjected to unsymmetrical earth pressure have been reported by Hamada et al. (2014, 2015). In addition to the results, this paper focuses on two seismic observation records during the seismic events on May 25 and 30, 2015. A magnitude of the event on May 25 is M5.5 and an epicenter of the event is near the monitored building, North Saitama. Whereas, those of the event on May 30 are M8.1 and far from the monitored building, Ogasawara islands, depth of 682 km. Comparing to two deferent type events, sectional forces on piles due to input acceleration are discussed. The earthquake having an epicenter far from the monitoring building has relatively long period and the ground deformation might be relatively large at the same acceleration level.

Accelerations of the building, dynamic sectional forces of the piles and dynamic earth pressure on both sides of the embedded foundation as well as that beneath the raft were observed. The maximum acceleration of 0.358 m/s^2 was observed at the foundation of the building foundation during the north Saitama event, May 25, 2015. Based on the seismic records, it was confirmed that a lateral inertial force of the building was closely related to shear forces and bending moments of the piles as well as frictional resistance beneath the raft. The ratio of the lateral load carried by the piles was discussed comparing the observed shear force of the piles to the estimated inertial force of the building.

2. MONITORED BUILDING AND SOIL CONDITIONS

The seismically monitored building, which is seven-story residential building with three basement floors, is located in Tokyo, Japan. The building subjected to unsymmetrical earth pressure is a reinforced concrete structure, 29.3m high, with a 71.4m by 36.0m footprint. Figure 1 shows a schematic view of the building and its foundation with a typical soil profile. The soil profile consists of fine sand layer just below the raft with SPT N-values from 10 to 20 and clay strata including humus between depths of 17 m and 24 m from the ground surface with unconfined compressive strength of about 140 kPa. Below the depth of 24 m, there lies a Pleistocene fine sand layer with SPT N-values of 40 or higher. The shear wave velocities derived from a P-S logging system were about 200 m/s between the depths of 17 m and 24 m, and 480 to 570 m/s in the sand layers below the depth of 24 m. The ground water table appears at a depth approximately equal to the basement level.

The average contact pressure over the raft was 159 kPa. If a conventional pile foundation were used for the building foundation subjected to unsymmetrical earth pressure, the piles should carry large lateral load not only for seismic condition but also for ordinary condition, where a design horizontal seismic coefficient of "lateral load over building dead load" was 0.15 for ordinary condition and 0.34 for severe seismic condition.

On the other hand, if a raft foundation were used, clay layer below sand layer just below the raft has a potential of excessive settlement while the sand layer has enough bearing capacity for the dead load of the building and lateral frictional resistance between the raft and the subsoil can be reliable.

Consequently, a piled raft foundation consiting of cast-in-place concrete piles with 1.2 m in diameter and 12.2 m in length was employed, where the lateral load can be resisted by both the piles and the frictional resistance beneath the raft. Natural frequency of the building is 1.7 Hz and ground natural frequancy is 4Hz at the lower ground surface and 2Hz at the higher ground surface assumed from shear wave velocity (200 m/s) and thickness of the strata (12m and 25m).

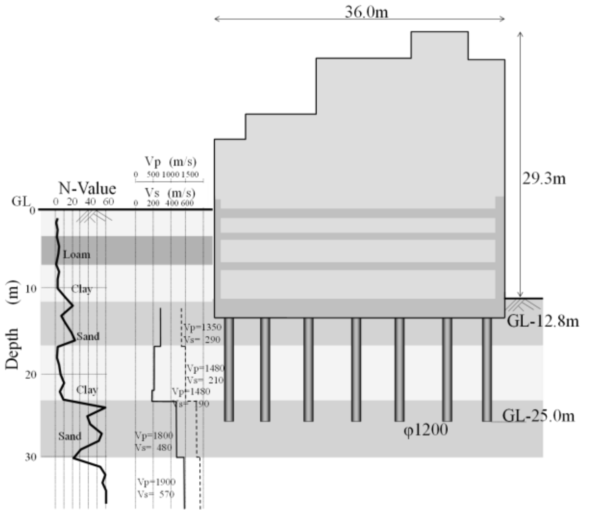


Figure 1 Schematic view of monitored building and foundation with soil profile

3. INSTRUMENTATION

Figure 2 and 3 show the layout of the piles with locations of monitoring devices. Axial forces and bending moments of the piles were measured by a couple of LVDT-type strain gauges on Pile 2D (2-D street), Pile 5G (5-G street) and Pile 5D (5-D street). Eight earth pressure cells and a pore-water pressure cell were installed beneath the raft around the instrumented piles. Three sections of Pile 5D at depths of 1.0 m, 2.0 m and 9.14 m below the pile head and those of Pile 5G at depths of 1.0 m, 1.7 m and 8.19 m were measured during earthquakes.

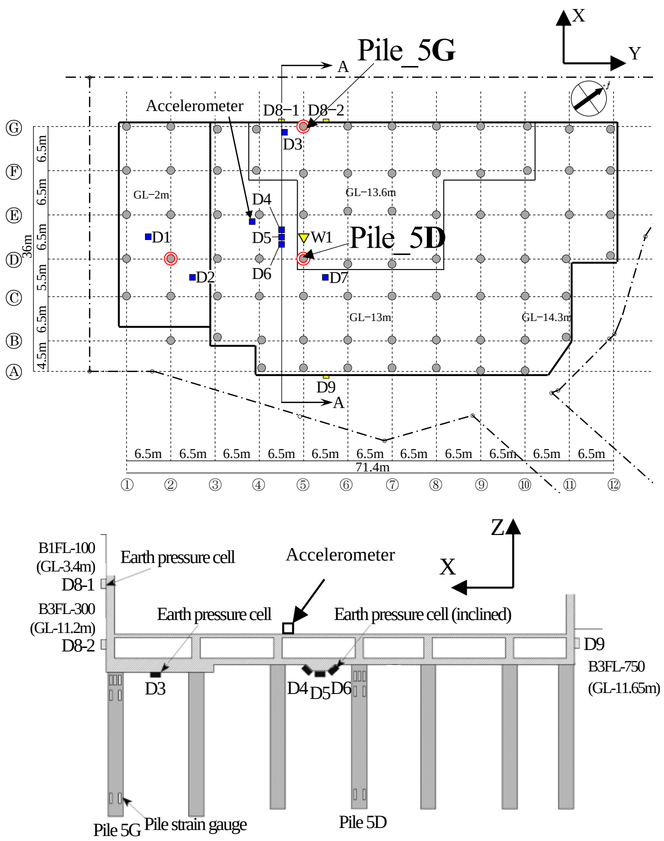


Figure 2 Foundation profile with locations of monitoring devices

Earth pressure cells of D4 and D6 were set obliquely on the soil around Pile 5D, as shown in Photo 1, in order to evaluate a frictional resistance beneath the raft by the difference of the earth pressure from the two earth pressure cells. Earth pressure cells of D8-1, D8-2 and D9 were set on the embedded side wall in order to evaluate a lateral force acting on the side wall of the building.

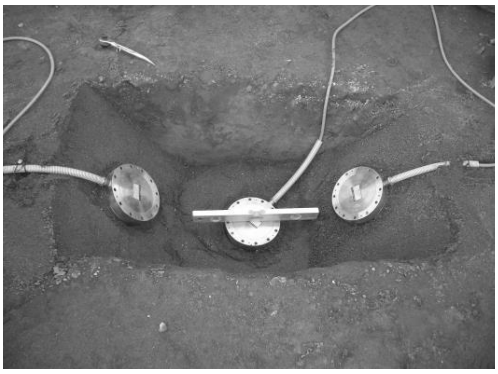


Photo 1 Inclined setting earth pressure cells (D4, D5 and D6)

As for the seismic observation, the NS, EW and UD accelerations of the building on the third basement floor (B3F) was recorded by triaxial servo accelerometers. The horizontal components of the triaxial accelerometer were oriented to the longitudinal direction and the transverse direction of the building as shown in Figure 2. In this paper, the transverse direction and the longitudinal direction of the building are called X-direction and Y-direction, respectively. The axial forces and the bending moments of two piles, 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. The triggering acceleration is 0.004 m/s^2 on the B3F and the sampling rate is employed at 100 Hz. Minimum available values of acceleration, strain and earth pressure are 2.4×10^{-4} m/s^2 , $1.0\times10^{-4}\mu$ and 5.0×10^{-6} kPa, respectively. Measuring system is consisted of IC Card Data Logger, Dynamic Amplifier and Power Unit as shown in Table 1 and Photo 2.

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:200, 300kPa
Piezometer	LVDT, Capacity:100kPa

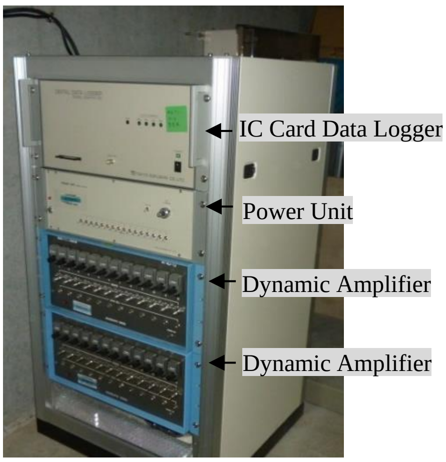
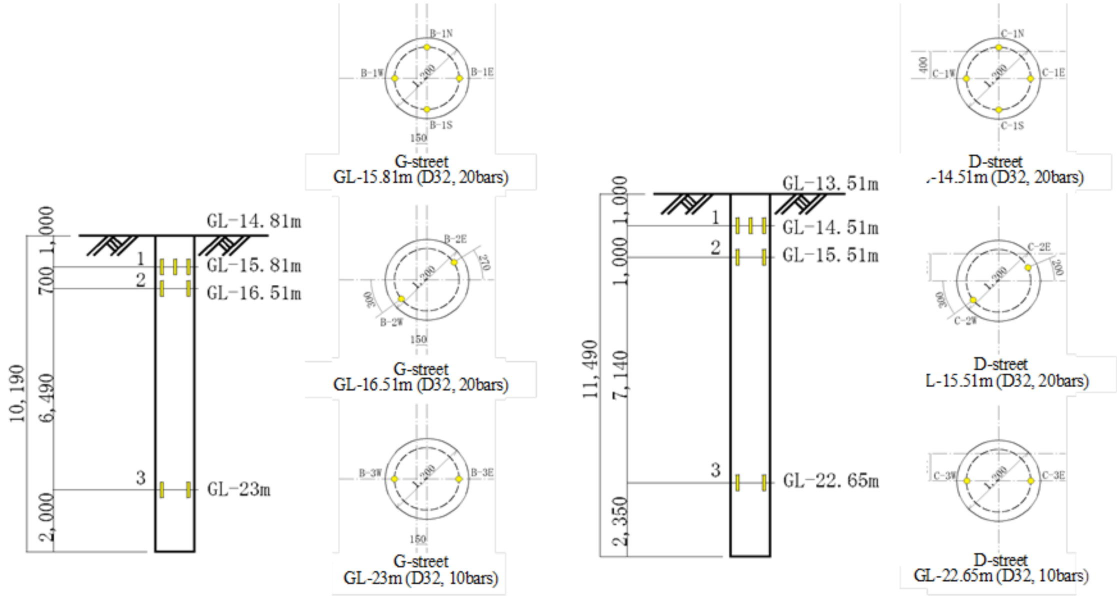


Photo 2 Layout of measuring system



(a) Pile 5G (b) Pile 5D

Figure 3 Locations of strain gauges on monitored piles

4. LONG-TERM STATIC MEASUREMENTS

Figure 4 shows the time-dependent load sharing among the pile load (kPa), the earth pressure and the water pressure in the tributary area of Pile 5D. The earth pressure is an average of the measured values from D7 and D5. The pile load (kPa) is estimated by the axial force of the pile divided by the tributary area of 39 m^2. The ratio of the load carried by the pile to the total load is 40% (42%) at the end of the construction and 47% (50%) about five years after that time. Here, the value in parentheses is the ratio of the load carried by the pile to the effective load. The ratios were almost same before and after the 2011 off the Pacific coast of Tohoku Earthquake which a seismic intensity at the observed building site was little less than 5.

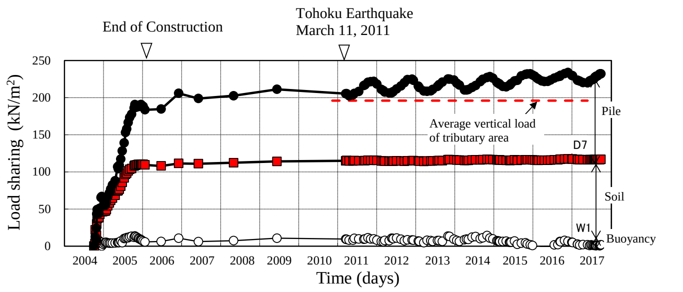
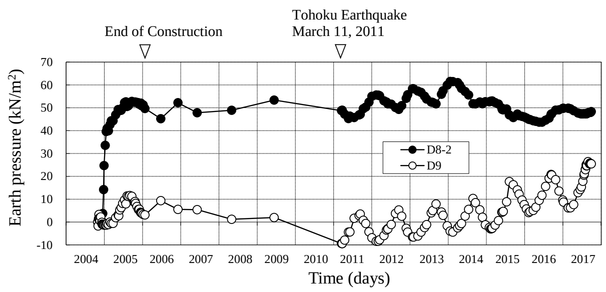


Figure 4 Time-dependent load sharing between Pile 5D and raft around the pile (5-D street)

Figure 5 shows the time-dependent earth presure acting on the embedded side walls. The earth pressure was stable after the earthquake. The value of earth pressure from D8-2 was found to be evaluated approximately as follows; an unit weight (17 kN/m^3) ×depth (11.2 m) ×coefficient of earth pressure K (0.3) is 57kPa.

The axial load of the pile and the earth pressures acting on side wall fluctuate according to a season due to temperature. The seasonal variation of the incremental earth pressures of D8-2, D9 shows opposite relation, that is positive and negative.



5. SEISMIC RESPONSE OF PILED RAFT FOUNDATION

5.1 Observed seismic events

Accelerations of the building, dynamic sectional forces of the piles and dynamic earth pressure on both sides of the embedded foundation as well as that beneath the raft were observed during 555 seismic events from March 23 in 2011 to Sep 26 in 2017, including an earthquake with a magnitude of M8.1. The maximum acceleration of 0.358 m/s^2 was observed on the building foundation. Figure 6 shows observed maximum accelerations of these seismic events and Figure 7 shows the number of the events every month. It can be seen that the number of the events decreased gradually after April, 2011.

Figure 8 shows locations of the monitored building and epicenters of relatively large seismic events. Large earthquakes of April 11 and 16, 2011, just after the Pacific coast of Tohoku Earthquake have attacked the monitored building site. This paper focuses on the seismic event on May 25 and 30, 2015.

5.2 Observed seismic responses of foundation

Figure 9 shows the time histories of the measured accelerations during the seismic event on May 25 and 30, 2011. A magnitude of the event on May 30 is M8.1 and an epicenter of the event is Ogasawara ocean area. Those of the event on May 25 are M5.5 and North Saitama, in which the maximum acceleration of 0.358 m/s^2 was recorded in X-direction.

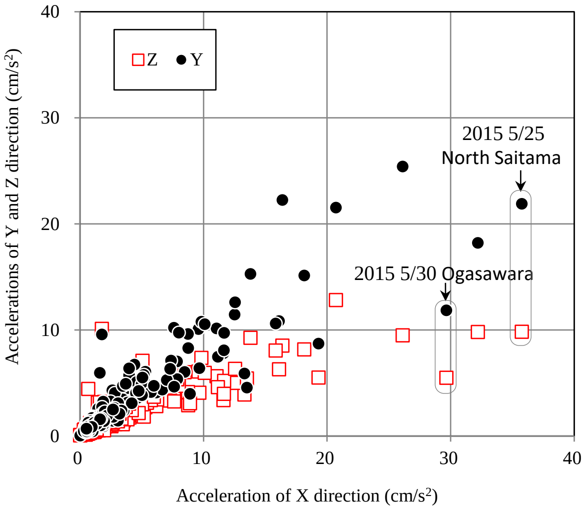


Figure 6 Maximum accelerations of seismic events

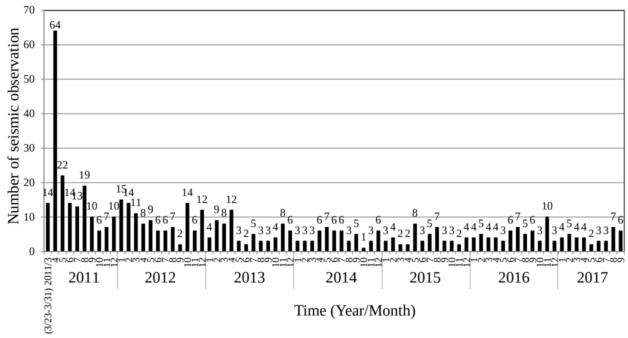


Figure 7 Number of seismic event per month

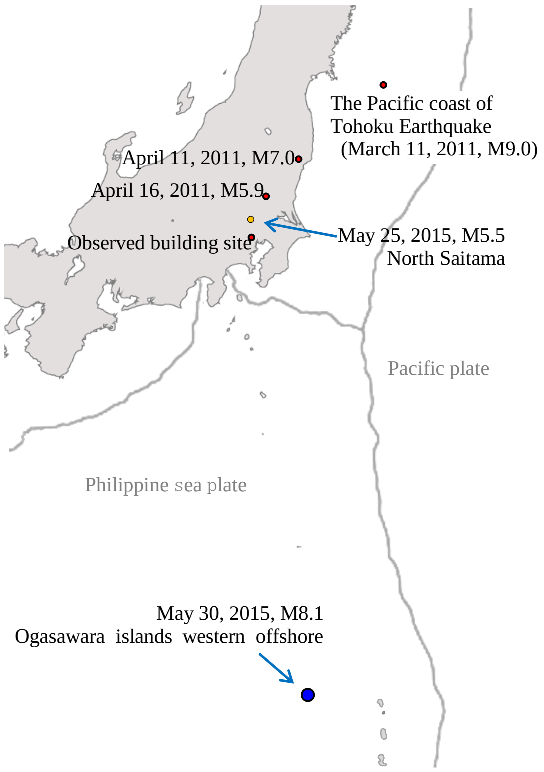
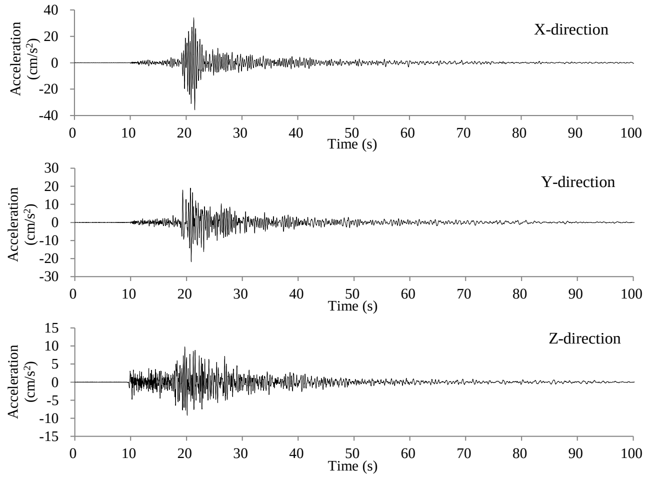
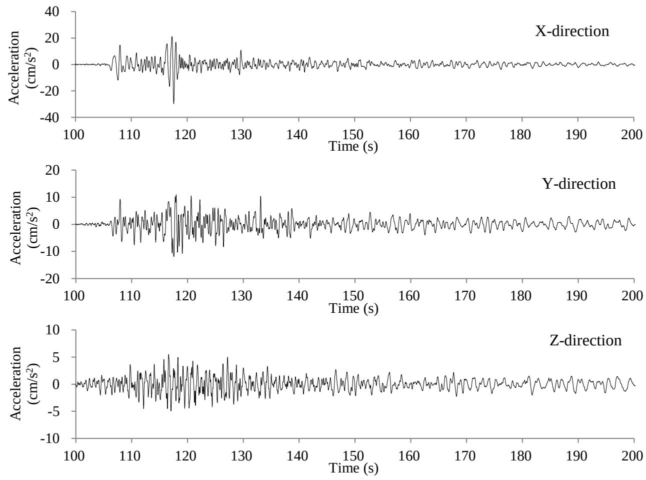


Figure 8 Locations of monitored building and epicenters of seismic events



(a) North Saitama, May 25, 2015 (M5.5)



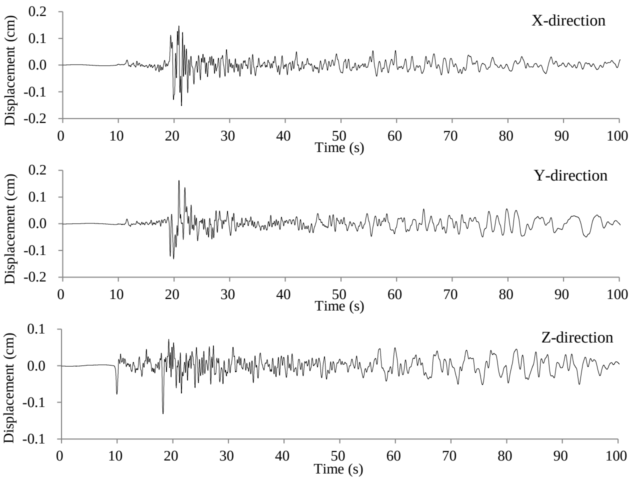
(b) Ogasawara, May 30, 2015 (M 8.1)

Figure 9 Time histories of the measured accelerations at B3F

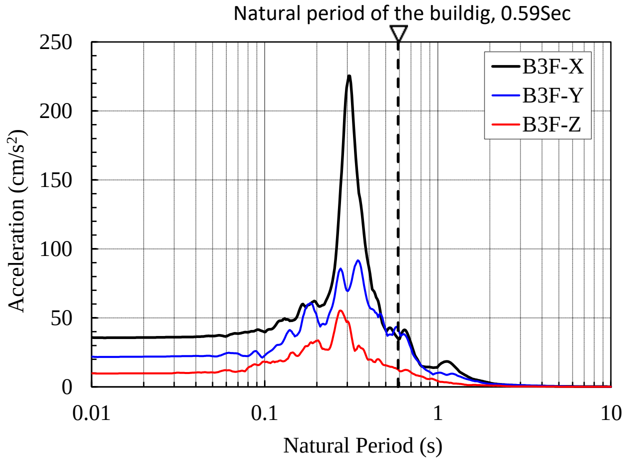
Figure 10 shows the time histories of the displacements during these events which were calculated by double-integration of the monitored accelerations. The Ogasawara earthquake includes so long period waves that the displacements are larger than those at the event on North Saitama. Peak horizontal displacements in X-direction were about 1.5 mm and 13.3 mm during North-Sitama event and Ogasawara event, respectively. Figure 11 shows the acceleration response spectrum of the observed accelerations. A natural period of the building is 0.59 sec. The domain periods of the input motion of North Saitama and Ogasawara are 0.3 sec and 0.7 sec, respectively. Therefore, it is considered that upper part of the building would be oscillating during Ogasawara event larger than during North Saitama event in X-direction. The building would be oscillated at the first mode during Ogasawara event, whereas as the second mode during North-Saitama event.

Figure 12 shows the relationship between peak accelerations and incremental peak strains on the monitored piles during 555 events. The peak strains almost depend on peak accelerations. However, the peak acceleration during the North Saitama event is larger than that during the Ogasawara event, whereas the peak strains during the former event are smaller than those during the later event.

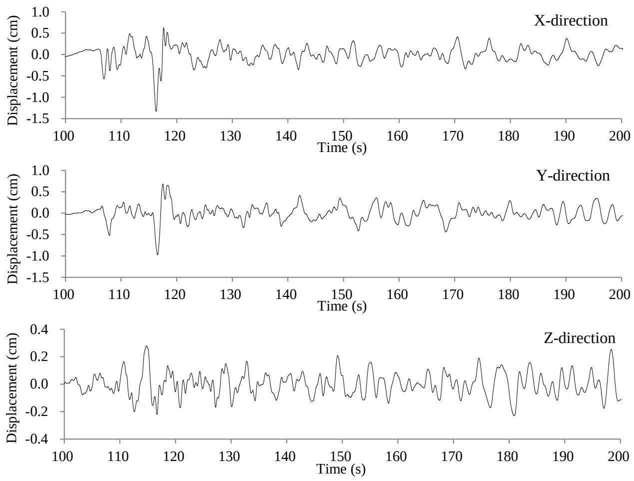
Figures 13 and 14 show the time histories of accelerations, sectional forces of the piles and earth pressures amplified including the main shock during the North Saitama event and the Ogasawara event, respectively.



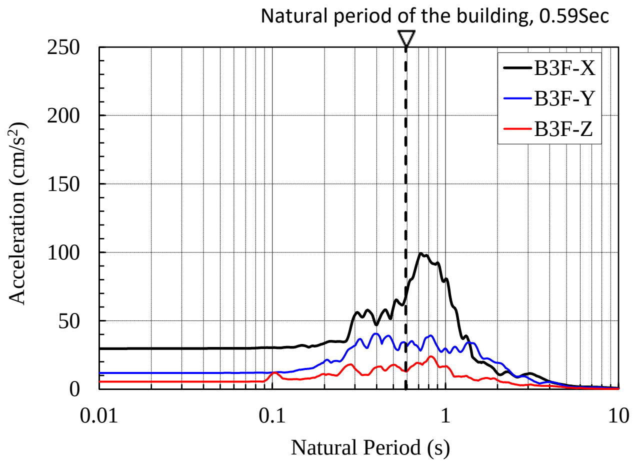
(a) North Saitama, May 25, 2015 (M5.5)



(a) North Saitama, May 25, 2015 (M5.5)



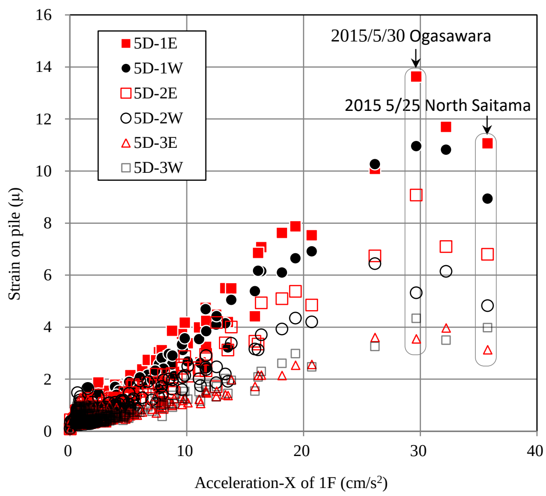
(b) Ogasawara, May 30, 2015 (M 8.1)



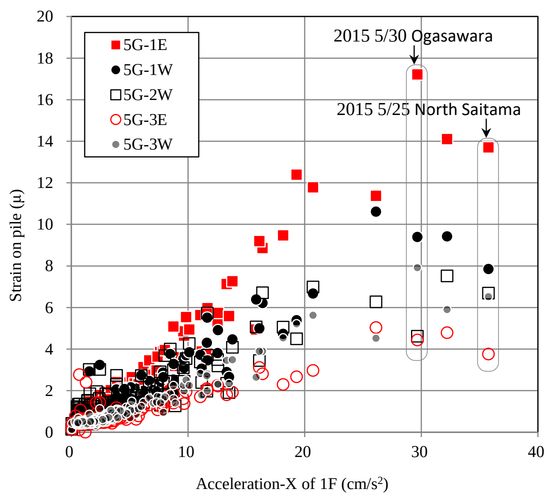
(b) Ogasawara, May 30, 2015 (M 8.1)

Figure 10 Time histories of the displacements at B3F

Figure 11 Acceleration response spectrum (h=5%)



(a) Pile 5D



(b) Pile 5G

Figure 12 Peak strain on monitored piles

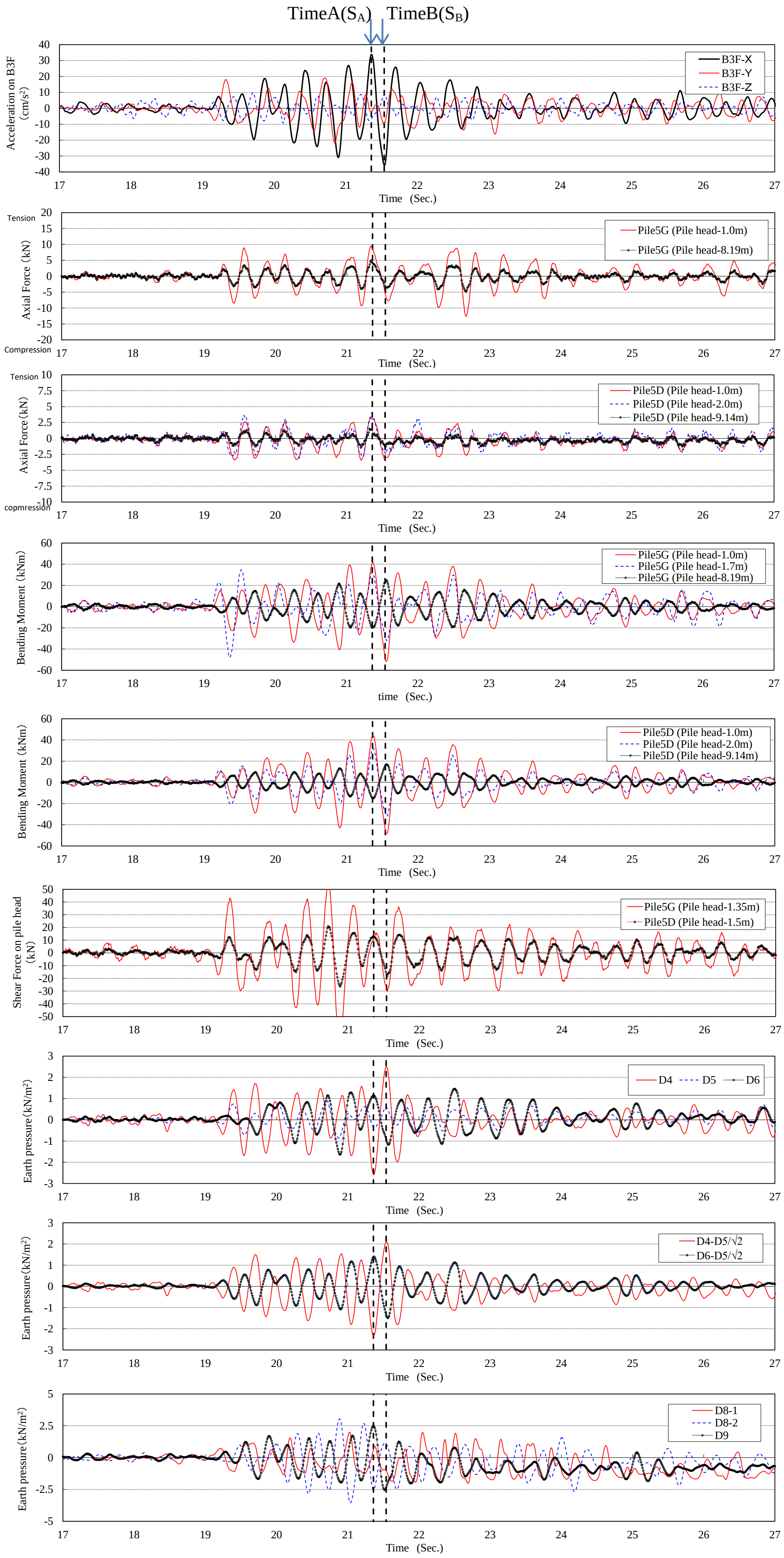


Figure 13 Time histories of accelerations, sectional forces of piles and earth pressures during North Saitama event (May 30, 2015)

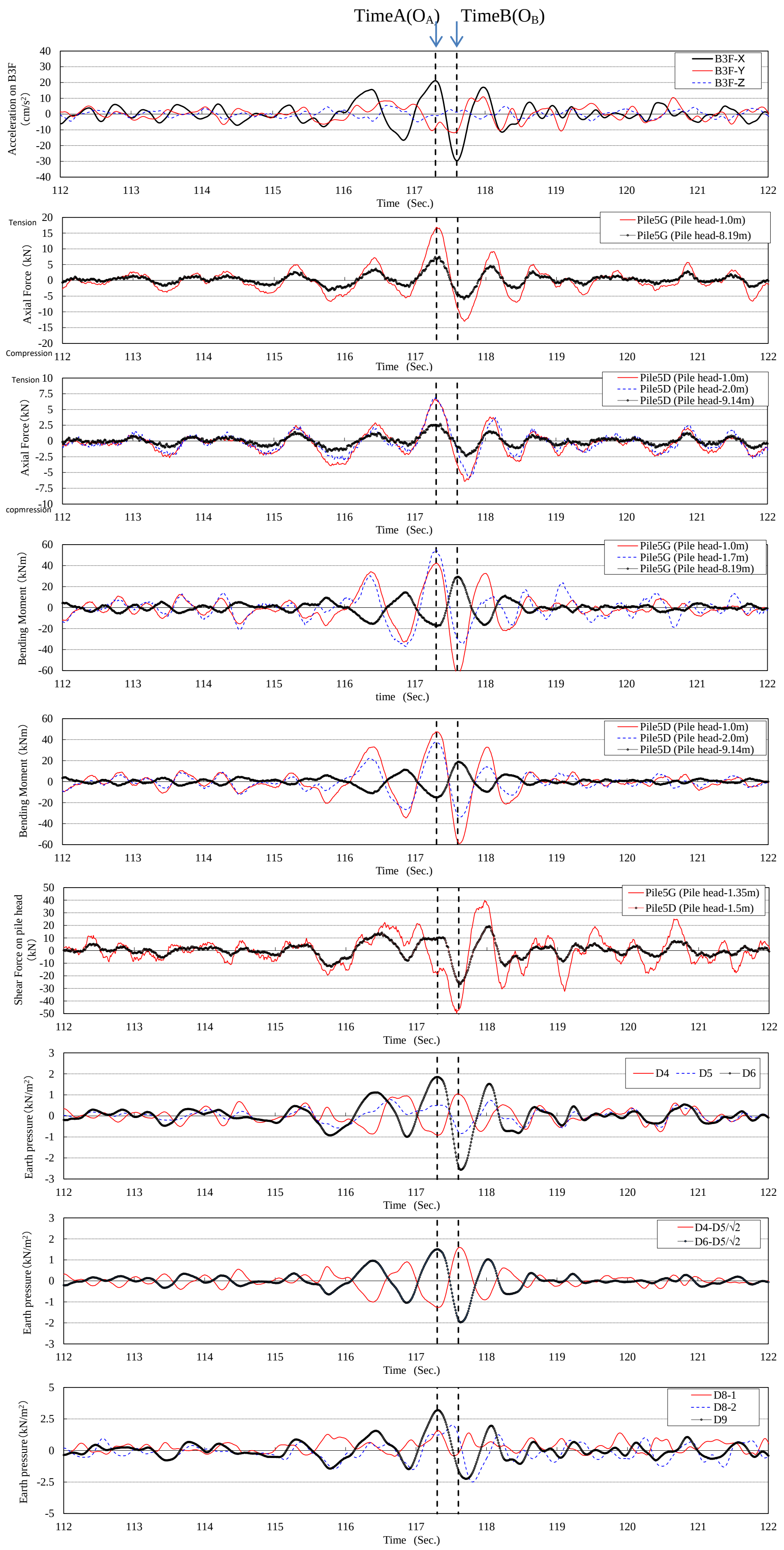


Figure 14 Time histories of accelerations, sectional forces of piles and earth pressures during Ogasawara event (May 25, 2015)

The two dashed lines indicate the time when the inertial force of building in X-direction was maximum and minimum, i.e., time of 21.36 sec (Time A) and 21.54 sec (time B) at North Saitama event. The sectional forces were estimated from the strains measured at the steel reinforcing bars in the piles. The bending moments were calculated using the measured strains from a couple of strain gauges. The shear forces were calculated from dividing the difference between the two sectional bending moments by the distance of the two sections. Young's modulus of concrete was assumed to be 21 GN/m^2.

Maximun bending moments at the pile head were about 50 kNm and 60 kNm for both Pile 5D and Pile 5G during North-Sitama event and Ogasawara event, respectively. However the shear force of pile 5G was larger than that of pile 5D. Here, the bending moment of pile 5G at the pile head (-1.7m) was estimated from one strain gauge by assuming the axial force at the pile head (-1.7m) to be that at the pile head (-1.0m), because the other gauge didn't work well.

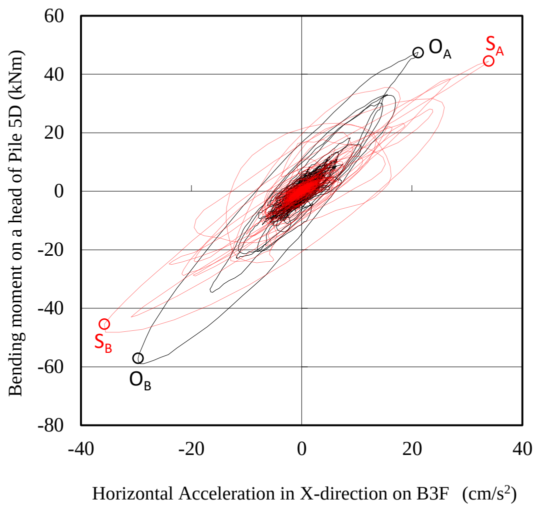
Although the values of earth pressure from the inclined setting earth pressure cells, D4 and D6 were not symmetrical, the modified values of earth pressure in which the vertical component of earth pressure from D5 was removed, i.e., D4-D5/ √2 and D6-D5/ √2, were almost symmetrical. So, it was found that the frictional resistance beneath the raft could be estimated from the inclined setting earth pressure cells even though some error may be included.

Figure 15(a) and (b) show the relationship between the horizontal acceleration in X-direction and the bending moment of Pile 5D and Pile 5G at the pile head, the bending moment was closely related to the inertial force of the building. Time S_A, S_B, O_A and O_B indicated in these figures are corresponding to the time in Figures 13 and 14. The bending moments occurred by far earthquake, Ogasawara were larger than those by near earthquake, North Saitama. The oscillating at upper part of the building during Ogasawara event might be larger than those during North Saitama event judging from a relationship between a natural period of the building and domain periods of the input motion. However, it is considered that the bending moments are generated by not only inertial force of superstructure but also ground deformation which is large during far earthquake.

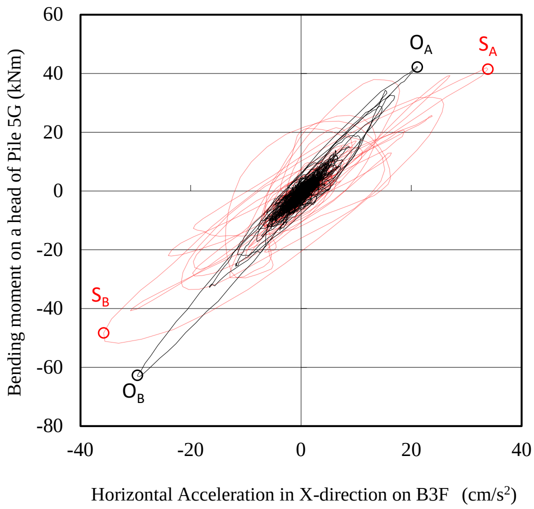
Figure 16(a) and (b) show the relationship between the horizontal acceleration in X-direction and the shear force of Pile 5D and Pile 5G at the pile head. Inertial force of the building is apploximately estimated from multiplying the weight of the building by the horizontal acceleration of the building in Figure 2. When the horizontal acceleration of the building is 0.3m/s^2 and the vertical average weight of the building is 159kPa with the tributary area of Pile 5D of 39 m^2, the inertia horizontal force of the building aroud Pile 5D is estimated to be 190 kN (=0.3/9.8×159×39). So, the lateral load sharing ratio of pile is estimated to be about 10 % when the shear force of the pile head is 20 kN. Whereas 30 % around the Pile 5G by estimation the shear force at pile head, 60 kN and horizontal acceleration of the building, 0.3m/s^2.

At the time of O_A, the shear force at the pile head of Pile 5G was acted on opposite direction for the inertial force of the building. This situation is considered to be occuered due to ground deformation around the pile.

Figure 17 shows the relationship between the shear force at the pile head and the frictional resistance beneath the raft, (√2×(D6-D4)/2×tributary area, 39m^2). On another approach agaist Figure 16, the ratio of the lateral load carried by the pile can be directry esmitated from Figure 17. When the shear force of the pile is 20 kN, and frictional resistance beneath the raft is 100 kN, the lateral load shearing ratio of pile is estimated to be 17 % (=20/(100+20)). Althogh the above consideration may include some error, it was confirmed that most of the inertial force of the building was transferred to the subsoil through the raft.



(a) Pile 5D

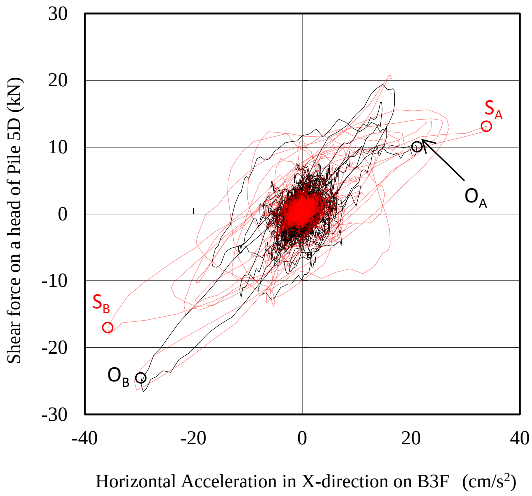


(b) Pile 5G

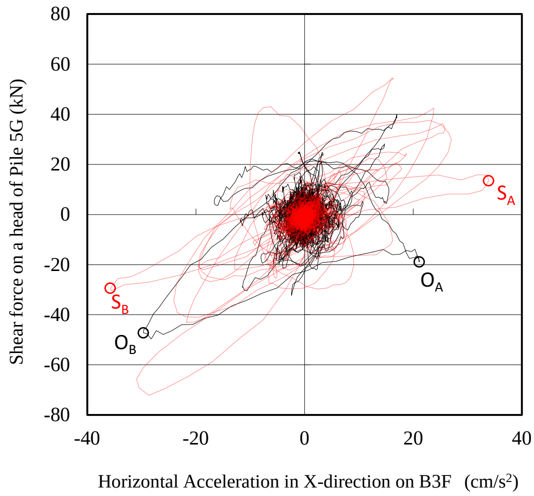
Figure 15 Bending moment on a pile head versus horizontal acceleration on the B3 floor

Figure 18 and 19 show the relationship between the horizontal acceleration in X-direction and the embedded earth pressure D8-2 and D9, the embedded resistances were almost working against the inertial force at the North Saitama event (S) but not against those at Ogasawara event (O). The phase differences can be seen in the far earthquake, Ogasawara. It must be occurred by ground deformation. The resistance of embedded side wall, D8-2 at time O_A is smaller than that at time S_A, so the resistance of Pile 5D and frictional forces beneath the raft at time O_A is larger than those at time S_A.

Figure 20 shows the relationship between the contact earth pressure beneath the raft D7 and axial load on the pile head Pile 5D. The incremental axial loads on pile head and contact earth pressures during Ogasawara event were significantly larger than those during North Saitama event. These values are close relationship at both events. So load sharing ratio for vertical load is stable. From the tributary area of Pile 5D of 39 m^2, the vertical incremental load at the raft aroud Pile 5D is estimated to be 23.4 kN (=0.6 kPa×39 m^2). So, the vertical load sharing ratio of pile is estimated to be about 20 % during earthquake when the incremental axial force of the pile head is 6 kN.



(a) Pile 5D



(b) Pile 5G

Figure 16 Shear force on a pile head versus horizontal acceleration on the B3 floor

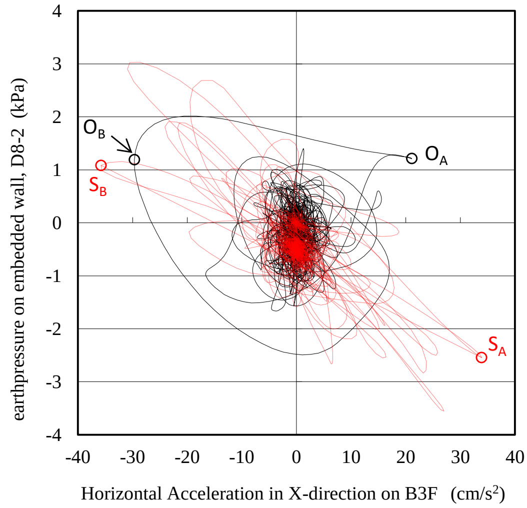


Figure 18 Earth pressure on embedded wall, D8-2 versus horizontal acceleration on the B3 floor

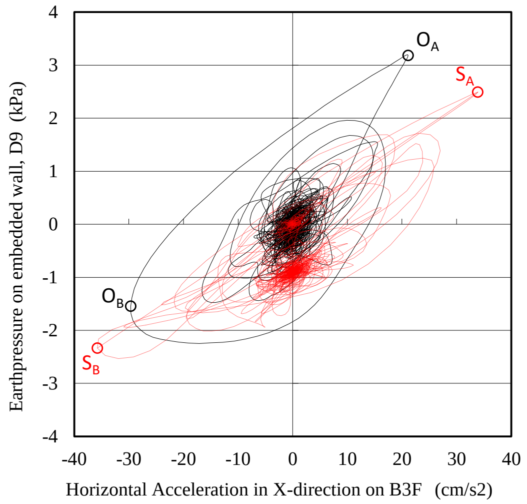


Figure 19 Earth pressure on embedded wall, D9 versus horizontal acceleration on the B3 floor

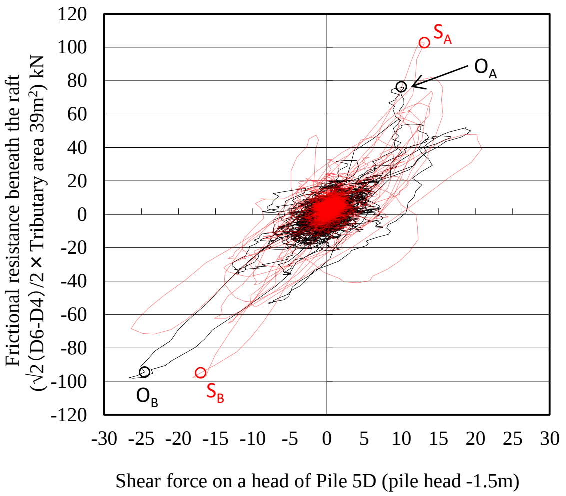


Figure 17 Frictional resistant beneath raft versus horizontal acceleration on the B3 floor

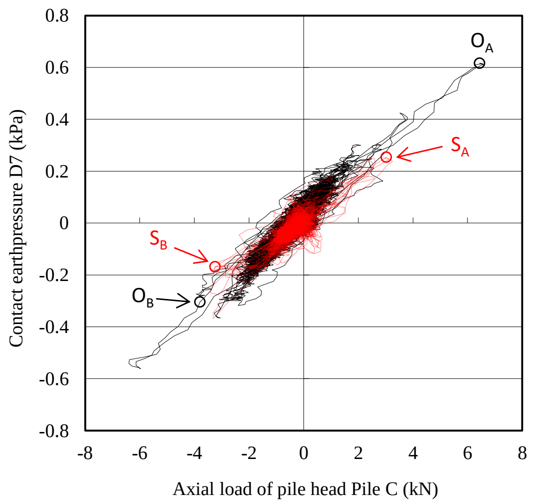
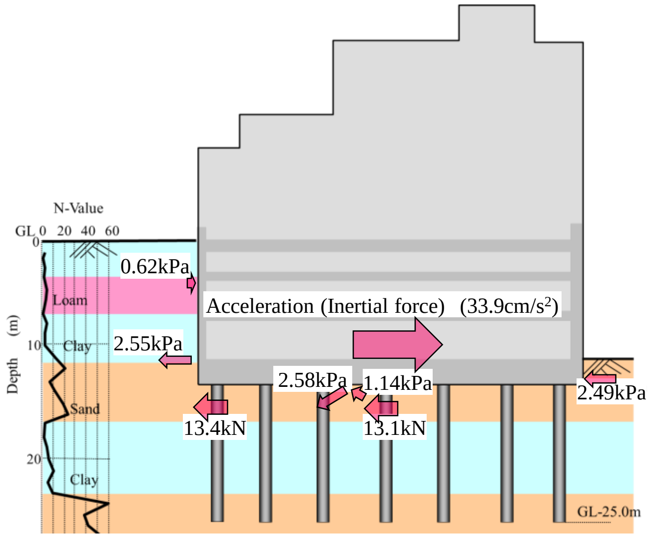


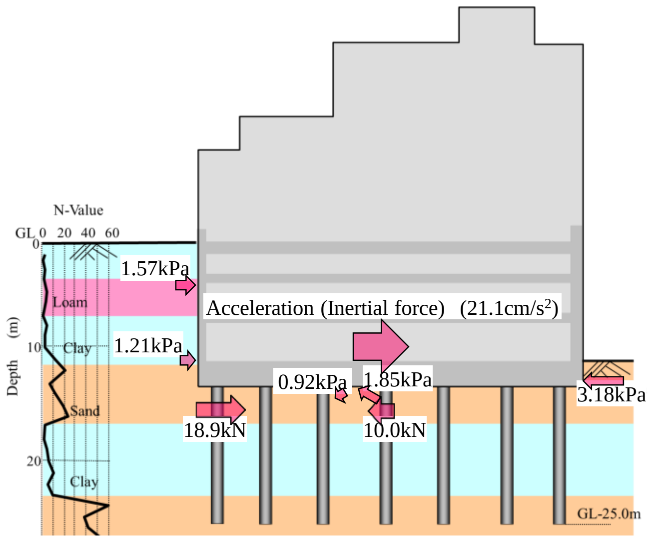
Figure 20 Contact earth pressure beneath raft versus axial load of pile head

5.3 Estimation of lateral load balance

Lateral load balances are shown in Figure 21 when the inertia force of the building is maximum. The times A in Figure 21 correspond to those shown in Figures 13 and 14. The shear force at the pile head and the frictional resistance beneath the raft and the embedded side walls were working against the inertia force of the building during near earthquake of North Saitama event. However, the tendency was different during far earthquake of Ogasawara event.



(a) North Saitama at time A



(b) Ogasawara at time A

Figure 21 Lateral load balance among inertial force, piles' shear force, frictional force and embedded earth pressures

6. CONCLUSION

Seismic observations on the piled raft foundation subjected to unsymmetrical earth pressure were performed just after the 2011 off the Pacific Coast of Tohoku Earthquake. Based on the two different types of seismic records due to near earthquake and far earthquake, it was found as follows;

1) A lateral inertial force of the building was supported by frictional resistance beneath the raft as well as shear forces of piles. The frictional resistance could be measured by earth pressure cells set obliquely on the soil just beneath the raft.
2) The incremental peak strains on piles due to far earthquake were larger than those due to near earthquake, whereas the peak acceleration at far earthquake was smaller than that at near earthquake.
3) The bending moments on piles were closely related to the horizontal acceleration of the building. However, the relationship was different depending on seismic type. It means the bending moments due to far earthquake were larger than those due to near earthquake.
4) The embedded side walls were almost working against the inertia force during near earthquake which has short period waves at the main shock.
5) The lateral load sharing ratio of piles was estimated about 10 to 30 % of the inertial force of building from observed record. It was confirmed that most of the inertial force of the building was transferred to the subsoil through the raft.

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