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Seismic Performance of Piled Raft Subjected to Unsymmetrical Earth Pressure Based on Seismic Observation Records

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ABSTRACT

Seismic observations on piled raft foundation subjected to unsymmetrical earth pressure were conducted just after the 2011 off the Pacific coast of Tohoku Earthquake. 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 the seismic events and the maximum acceleration of 0.322 m/s^2 was observed on the building foundation. Based on the two seismic records, it was confirmed that a lateral inertial force of the building was transferred to the subsoil through the raft, the embedded side walls were almost working against the inertia force. 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 20 %.

Introduction

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. In the last decade, 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. (2012a) 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. This paper presents two seismic observation records on a piled raft foundation subjected to unsymmetrical earth pressure during the events just after the 2011 off the Pacific Coast of Tohoku Earthquake. Accelerations of the building, dynamic sectional forces of the piles and dynamic earth pressure on both sides of the

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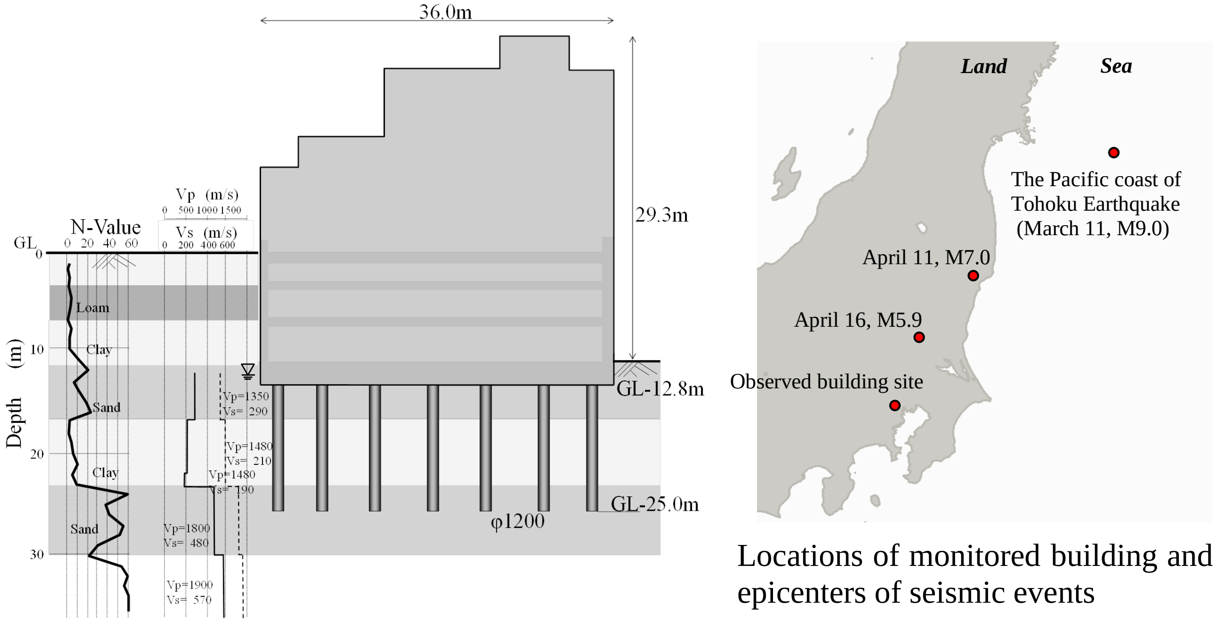
embedded foundation as well as that beneath the raft were observed. The maximum acceleration of 0.322 m/s^2 was observed at the foundation of building foundation. Based on the seismic records, it was confirmed that a lateral inertial force of the building was closely related to shear forces and bending 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 and the estimated inertial force of the building.

The static and seismic observation records have been reported by Hamada et al. (2012b, 2014). In addition to the results, the relationship between the resistances of embedded side walls and the sectional forces of the piles was focused on and discussed in this paper.

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 and a location of the building including monitored events epicenters. 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 diluvial fine sand layer with SPT N-values of 40 or higer. 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.



Locations of monitored building and epicenters of seismic events

Figure 1. Schematic view of building and foundation with soil profile and locations of monitored building and seismic events

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).

Instrumentation

Figure 2 shows the layout of the piles with locations of monitoring decices. 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.

Earth pressure cells of D4 and D6 were set obliquely on the soil around Pile 5D 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.

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 accelerometers. 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.

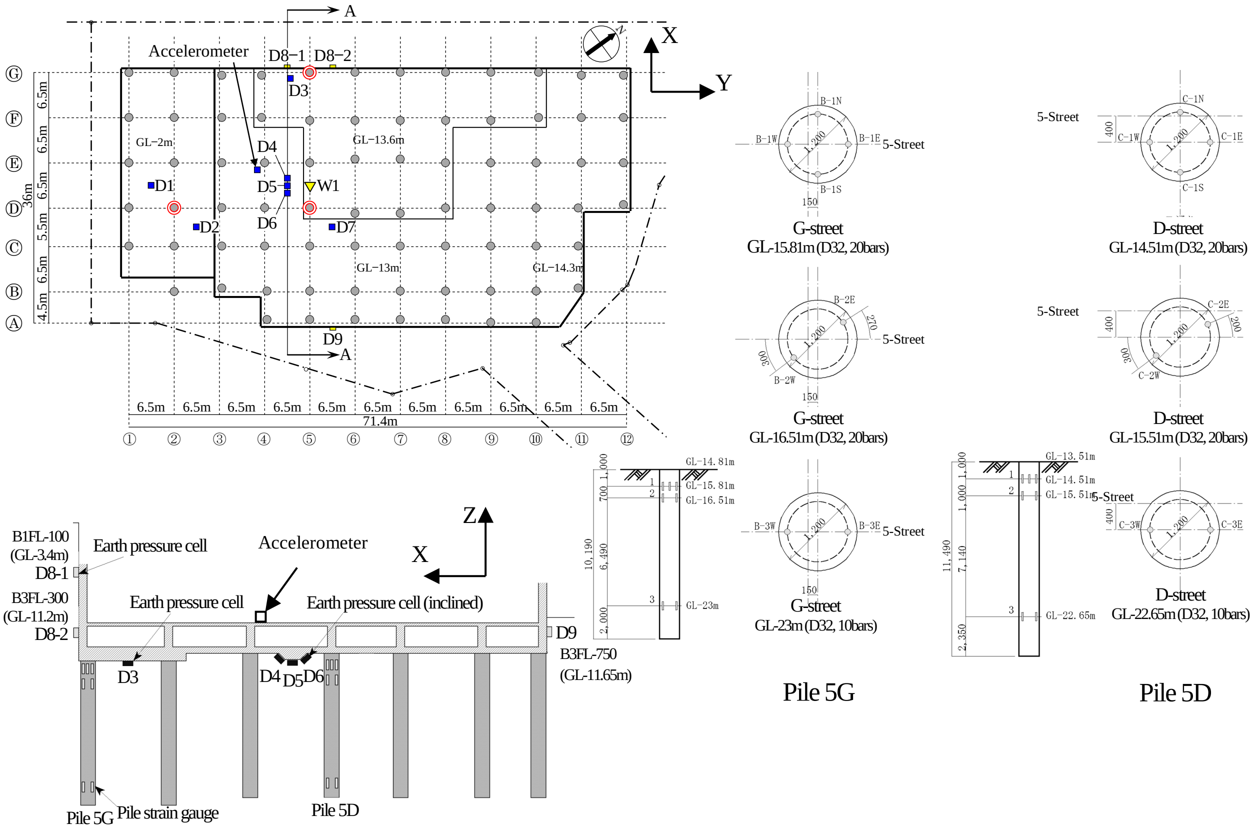


Figure 2. Foundation profile with locations of monitoring devices

Long-term Static Measurement Results

Figure 3 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 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.

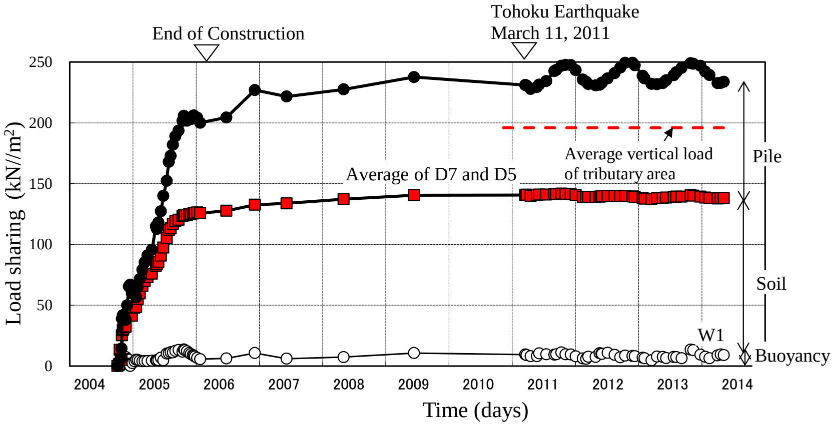


Figure 3. Time-dependent load sharing between Pile 5D and raft around the pile (5-D street)

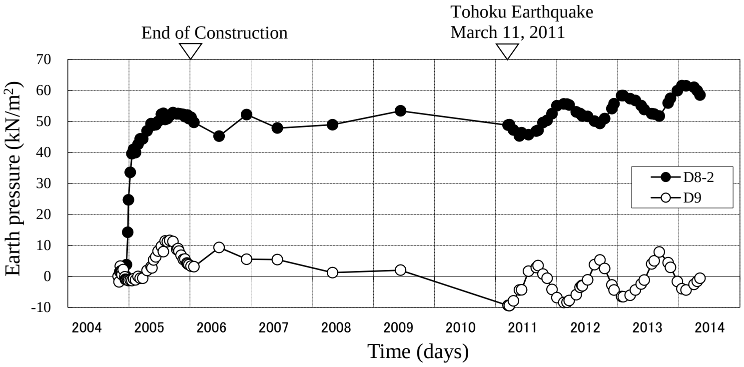


Figure 4. Time-dependent earth pressure acting on side walls

Observed Seismic Response of Piled Raft Foundation

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 371 seismic events from March 23 in 2011 to April 30 in 2014, including an earthquake with a magnitude of Me7.1. The maximum acceleration of 32.2 cm/s^2 was observed on the building foundation. Figure 5 shows the time histories of the measured accelerations during the seismic event on April 11 and 16, 2011. A magnitude of the event on April 11 is M7.0 and an epicenter of the event is Fukushima coastal area. Those of the event on April 16 are M5.9 and south Ibaraki, in which the maximum acceleration of 0.322 m/s^2 was recorded in X-direction.

Figure 6 shows the time histories of accelerations, sectional forces of the piles and earth pressures amplified between 22 and 25 s including the main shock. The three dashed lines indicate the time when the inertial force of building in X-direction and sectional forces of Pile 5D were large ,i.e., time of 23.19 sec (Time A), 23.50 sec (time B) and 23.84 sec (Time C). 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. Young’s modulus of concrete was assumed to be 21 GN/m^2.

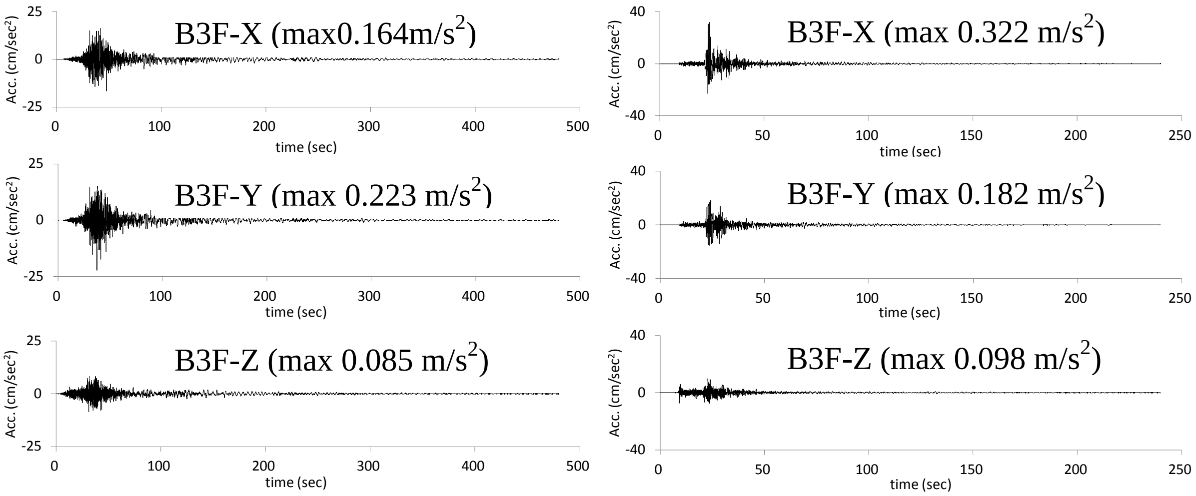


Figure 5. Time histories of accelerations (Left: April 11, 2011, Right: April 16, 2011)

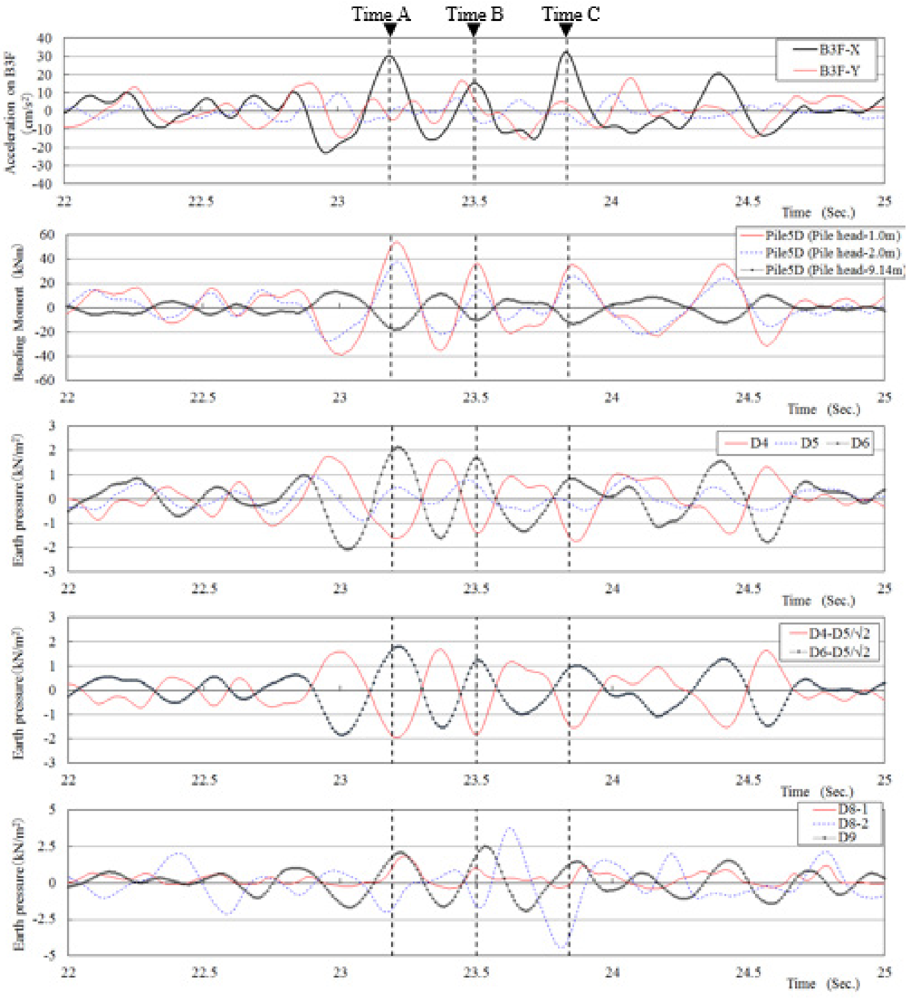


Figure 6. Time histories of accelerations, sectional forces and earth pressures (April 16, 2011)

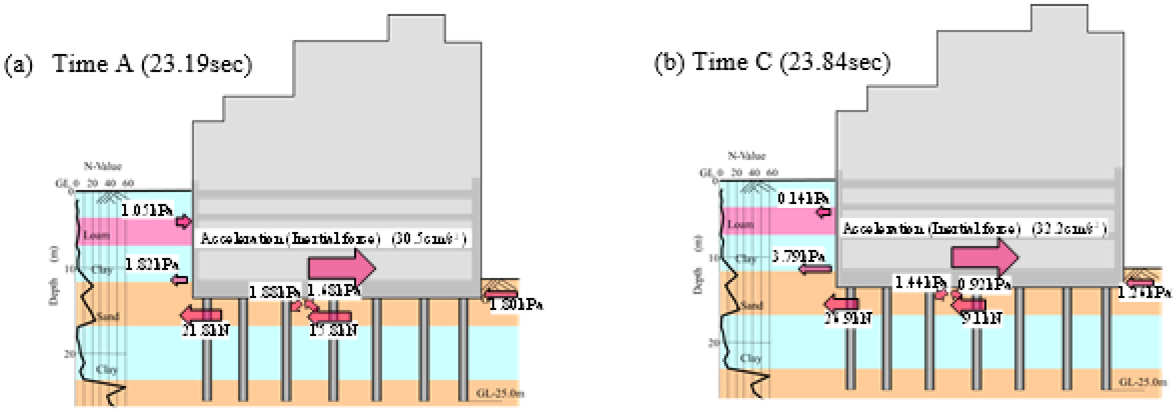
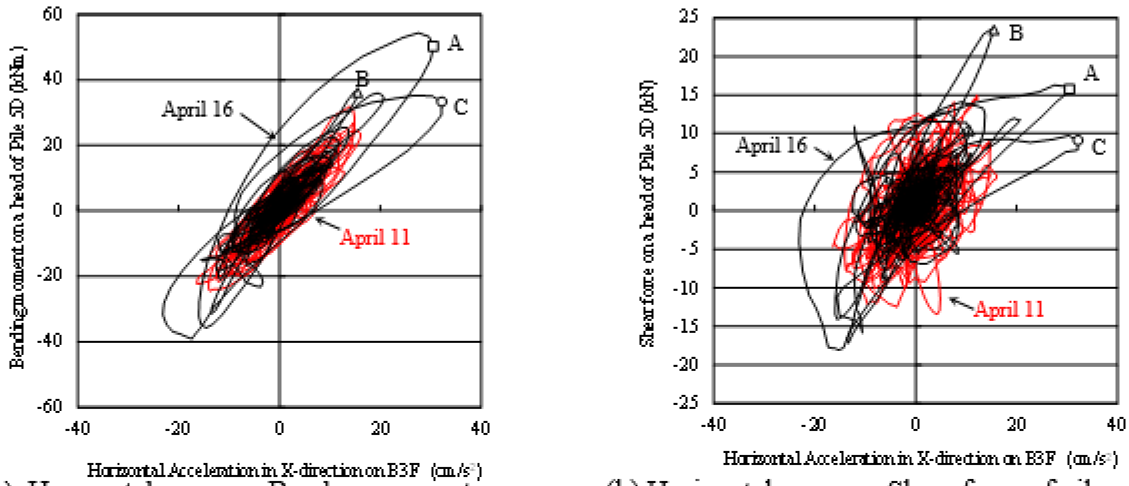


Figure 7. Load balance among inertial force, piles' shear force and frictional force

Maximun bending moments at the pile head were about 50 kNm for Pile 5D. Although the values of earth pressure from the inclined setting earth presure 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 7 shows load balance among inertial force of the building, piles' shear forces and frictional forces beneath the raft at time A and C. The shear forces were calculated from dividing the difference between the two sectional bending moments by the distance of the two sections. Although the horizontal accelerations at time A and B are almost same of 0.03 m/s^2, the embedded resistances and the bending moments are significantly different at each time.

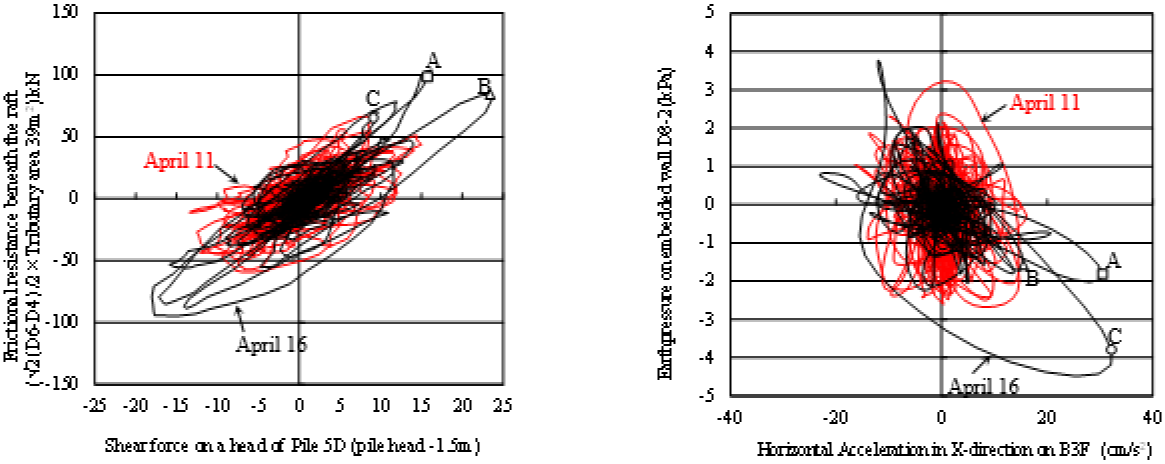
Figure 8(a) shows the relationship between the horizontal acceleration in X-direction and the bending moment of Pile 5D at the pile head, the bending moment was closely related to the inertial force of the building. Time A, B and C indicated in these figures are corresponding to the time in Figs. 6 and 7. Figure 8(b) shows the relationship between the horizontal acceleration in X-direction and the shear force of Pile 5D at the pile head (-1.5 m). Figure 8(c) 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). Inertial force of the building is apploximately estimated from multiplying the weight of the building by the horizontal acceleration of the building in Figure 6. Figure 8(d) shows the relationship between the horizontal acceleration in X-direction and the embedded earth pressure (D8-2), the embedded resistances were almost working against the inertial force at the event on April 16 but not against those on April 11. The resistance of embedded side wall at time A is smaller than that at time C, so the resistance of Pile 5D and frictional forces beneath the raft at time A is larger than those at time C.

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.



(a) Horizontal acce. vs. Bending moment

(b) Horizontal acce. vs. Shear force of pile



(c) Shear force of pile vs. Frictional resistance

(d) Horizontal acce. vs. Embedded resistance

Figure 8. Relationship among horizontal acceleration, shear force at pile head, lateral resistance of raft and lateral resistance of embedded side wall (red line :April 11, black line : April 16)

On another approach, the ratio of the lateral load carried by the pile can be directry esmitated from Figure 8. 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 transfered to the subsoil through the raft.

Conclusions

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 seismic records, it was confirmed that a lateral inertial force of the building was supported by frictional resistance beneath the raft as well as shear forces of piles. The embedded side walls were almost working against the inertia force. When the resistance of the embedded side wall was large, the sectional forces of pile and frictional forces beneath the raft were small.

It was also found that lateral load sharing ratio of piles was estimated about 10 to 20 % of the inertial force of building from observed record. It was confirmed that most of the inertial force of the building was transfered to the subsoil through the raft.

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