Seismic Observation of Piled Raft Foundation Subjected to Unsymmetrical Earth Pressure
常時偏土圧を受けるパイルド・ラフト基礎の地震観測

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Summary

The purpose of this study is to clarify the seismic performance of piled raft foundations based on seismic observation records. Seismic observation on piled raft foundation on medium stiff sand, supporting a seven-story building with three basement floors, subjected to unsymmetrical earth pressure began just after the 2011 off the Pacific coast of Tohoku Earthquake. The seismically monitored building is 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 371 seismic events including an earthquake with a magnitude of Me7.1. The maximum acceleration of 0.322 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 supported by frictional resistance beneath the raft as well as shear forces of piles. It was also found that the ratio of the lateral load carried by the piles to the lateral inertial force of the building was estimated to be about 10 to 20 %.

Keywords: piled raft foundation, seismic observation, unsymmetrical earth pressure,
the 2011 off the Pacific coast of Tohoku Earthquake

梗 概

本研究の目的は，パイルド・ラフト基礎の地震時挙動を地震観測データより明らかにすることである。偏土圧を受ける基礎の地震観測は，2011年東北地方太平洋沖地震後に行った。観測した建物は砂地盤上に建つ7階建て，地下3階建ての建物である。偏土圧を受けるパイルド・ラフト基礎の地震観測を行い，マグニチュード7.1を含む371波の地震動に対して建物の加速度，杭の断面力および地下壁の側面土圧を計測した。基礎の最大加速度0.322m/s^{2}が観測された。建物に設置した地震計より建物慣性力を評価し，建物慣性力と杭頭せん断力を比較することで，基礎底面に流れた水平荷重を算定し，杭の水平荷重分担率は10～20%と評価された。

キーワード：パイルド・ラフト基礎，地震観測，偏土圧，2011年東北地方太平洋沖地震

1 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 (Watanabe et al.[1)], Horikoshi et al.[2)], Matsumoto et al.[3)], Katzenbach & Turek[4)], Matsumoto et al.[5)], Hamada et al.[6)]) and analytical studies (Kitiyodom & Matsumoto[7)], Hamada et al.[8)]) have been carried out. Mendoza et al.[9)] 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.[10)] and Hamada et al.[11)] had successfully recorded seismic response of piled raft foundation supporting a base-isolated building during the 2011 off the Pacific coast of

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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. Moreover, simulation analyses of the seismic behavior of the building using a detailed three dimensional finite-element model were performed (Onimaru et al.[12]), Hamada et al.[13]), Hamada et al.[14])). The simulation results show good agreement with the observed decrease in the input motion, which was reduced by the ground improvement, and the observed 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 seismic observation records on a piled raft foundation subjected to unsymmetrical earth pressure during the events 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 embedded foundation as well as that beneath the raft were observed during 371 seismic events including an earthquake magnitude of Me7.1. Seismic observation period was from March 23 in 2011 to April 30 in 2014. 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.[15]). The results after June 2012 were added in this paper and a seasonal variation of the long term static results were discussed.

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, 29.3 m high, with a 71.4 m by 36.0 m 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 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

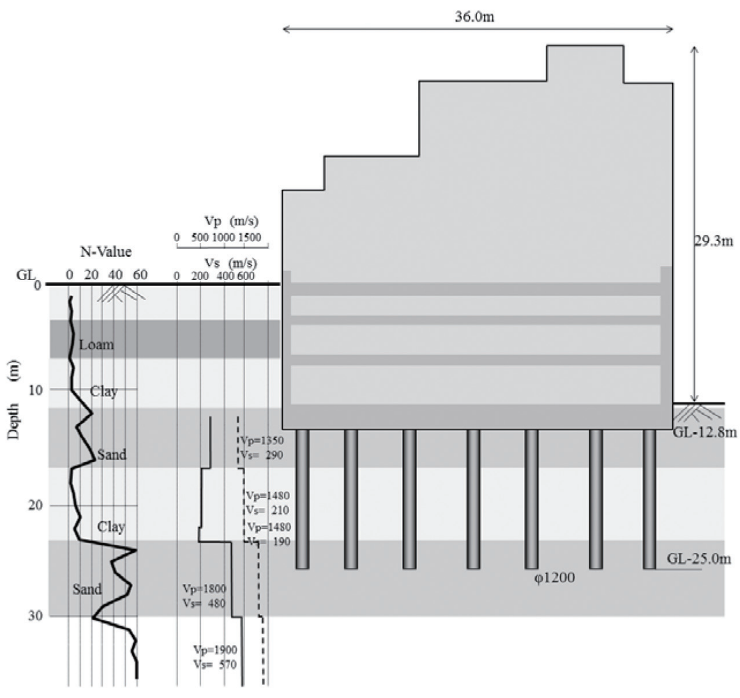


Fig. 1 Schematic view of building and foundation with soil profile

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 seismic intensity 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.

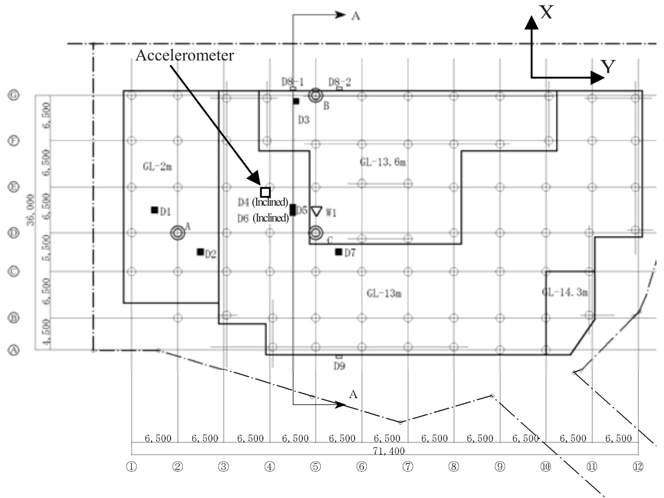
Consequently, a piled raft foundation consiting of cast-in-place concrete piles with 1.2 m in diameter and 12.2 m in length was employed, where the lateral load can be resisted by both the piles and the frictional resistance beneath the raft. Natural frequency of the building is 1.7 Hz and ground natural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

3 INSTRUMENTATION

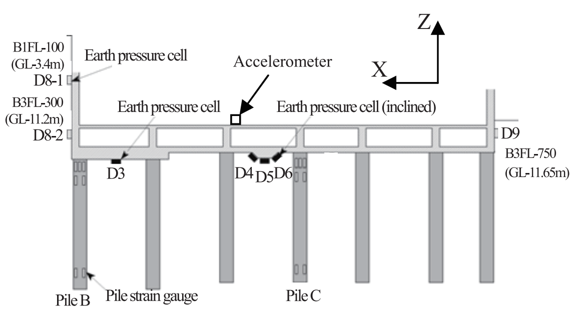
Figure 2 shows the layout of the piles with locations of monitoring decices. Axial forces and bending moments of the piles were measured by a couple of LVDT-type strain gauges on pile A (2-D street), pile B (5-G street) and pile C (5-D street). Eight earth pressure cells and a pore-water pressure cell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

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 Fig. 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



(a) Plane view



(b) Side view

Fig. 2 Foundation profile with locations of monitoring devices

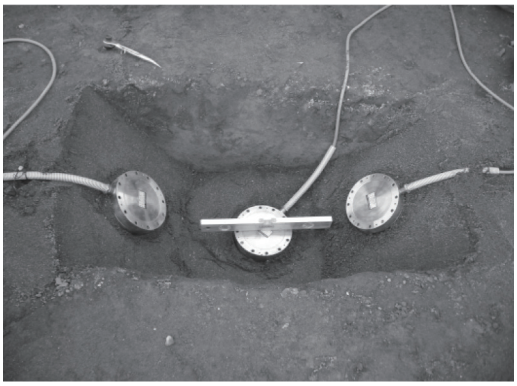


Photo 1 Inclined setting earth pressure cells

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, 1.0×10^{-4}μ 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 Property of measuring devices

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

4 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 C. 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.

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 57 kPa.

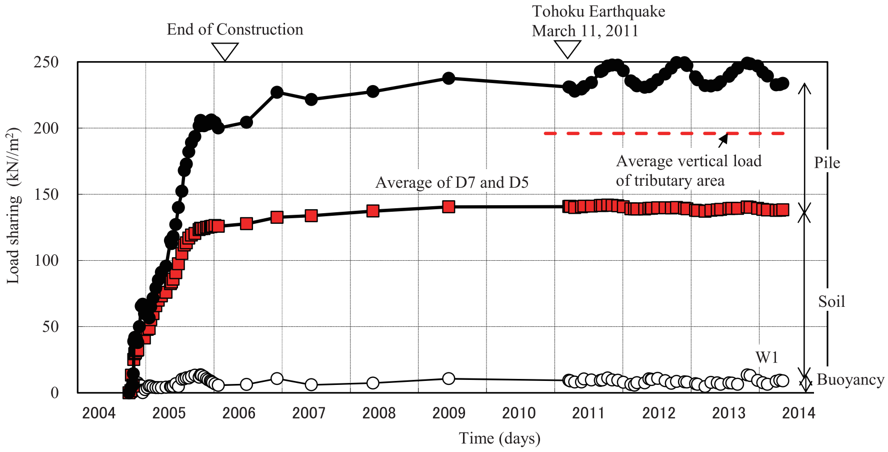


Fig. 3 Time-dependent load sharing between piles and raft around pile C (5-D street)

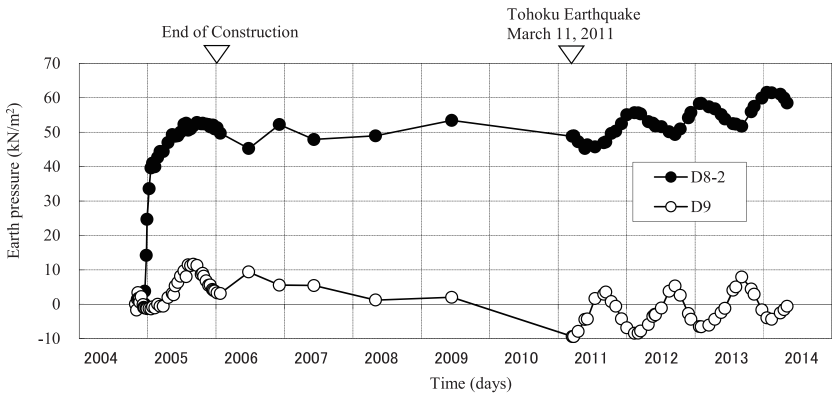


Fig. 4 Time-dependent earth pressure acting on side walls

The axial load of the pile and the earth pressures acting on side wall flactuate according to a season. 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

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 0.322 m/s^2 was observed on the building foundation. Figure 5 shows observed maximum accelerations of these seismic events and Fig. 6 shows the number of the events every month. It can be seen that the number of the events decreased gradually after April, 2011.

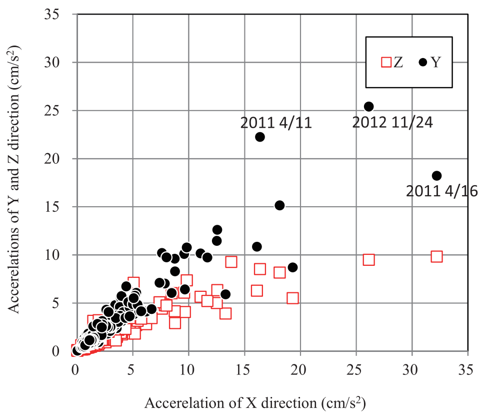


Fig. 5 Maximum accelerations of seismic events

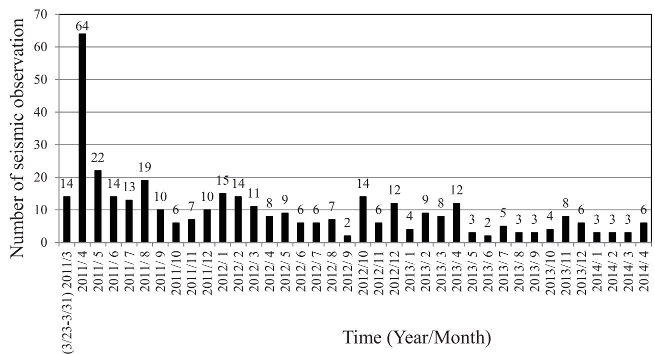


Fig. 6 Number of seismic event per month

5.1 Observed Seismic Response of Foundation

Figure 7 shows the time histories of the measured accelerations during the seismic event on April 16, 2011 with a magnitude of 5.9 and epicenter of south Ibaraki, in which the maximum acceleration of 0.322 m/s^2 was recorded in X-direction.

Figure 8 shows the time histories of accelerations, sectional forces of the piles and earth pressures amplified between 20 and 30 s including the main shock. The dashed lines indicate the time when the inertial force of building was maximum and minimum, i.e., time of 22.96 sec (Time B) and time of 23.84 sec (Time A), respectively.

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 and the shear forces were calculated from dividing the difference between the two sectional bending moments by the distance of the two sections. Young' modulus of concrete was assumed to be 2.1^E+7 kN/m^2.

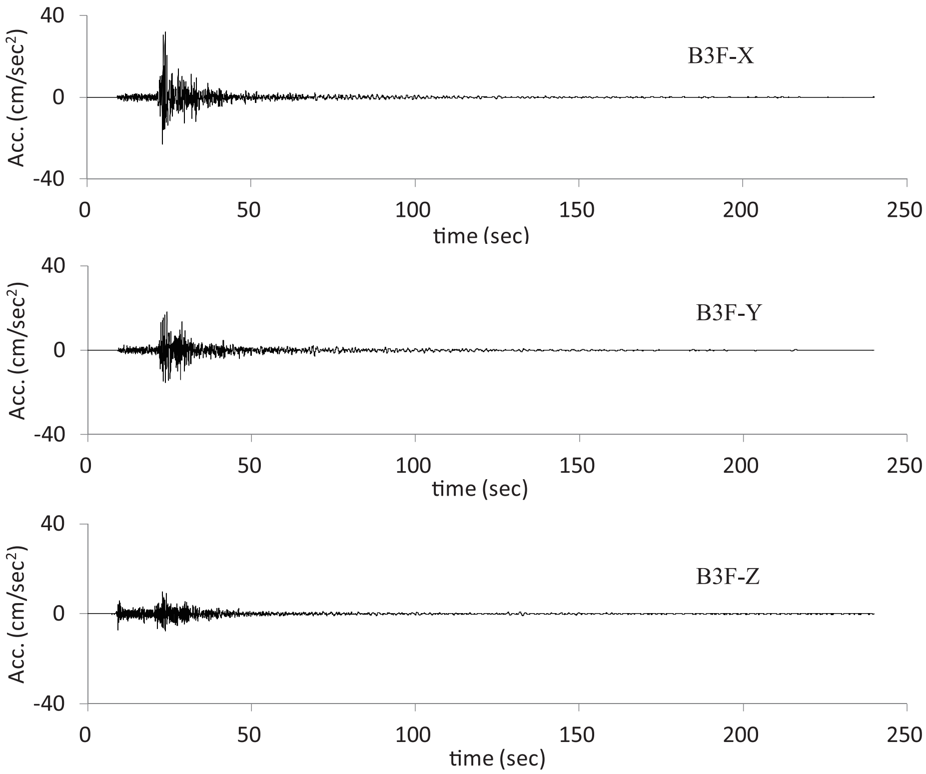


Fig. 7 Time histories of accelerations (April 16, 2011)

Maximun bending moments at the pile head were about 50 kNm for both piles B and C. However the shear force of pile B was larger than that of pile C. Here, the bending moment of pile B at the pile head (-1.7 m) was estimated from one strain gauge by assuming the axial force at the pile head (-1.7 m) to be that at the pile head (-1.0 m), because the other gauge didn’t work well. 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/$\sqrt{2}$ and D6-D5/$\sqrt{2}$, 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 9 shows the relationship between the horizontal acceleration in X-direction and the shear force of pile C at the pile head with spectra ratio. Figure 10 shows the relationship between the shear force at the pile head (-1.5 m) and the frictional resistance beneath the raft , ($\sqrt{2}$ × (D6-D4) /2 × tributary area, 39 m^2) with spectra ratio. Here, phase difference zero means positive correlation and 180 degree means negative correlation. Phase difference is almost zero degree at a frequency from 1 to 5 Hz.

Inertial force of the building is apploximately estimated from multiplying the weight of the building by the horizontal acceleration of the building in Fig. 9. When the horizontal acceleration of the building is 0.3 m/s^2 and the vertical average weight of the building is 159 kPa with the tributary area of pile C of 39 m^2, the inertial horizontal force of the building aroud pile C is estimated to be 190 kN (=0.03/9.8 × 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.

On another approach, the ratio of the lateral load carried by the pile can be directry esmitated from Fig. 10. 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.

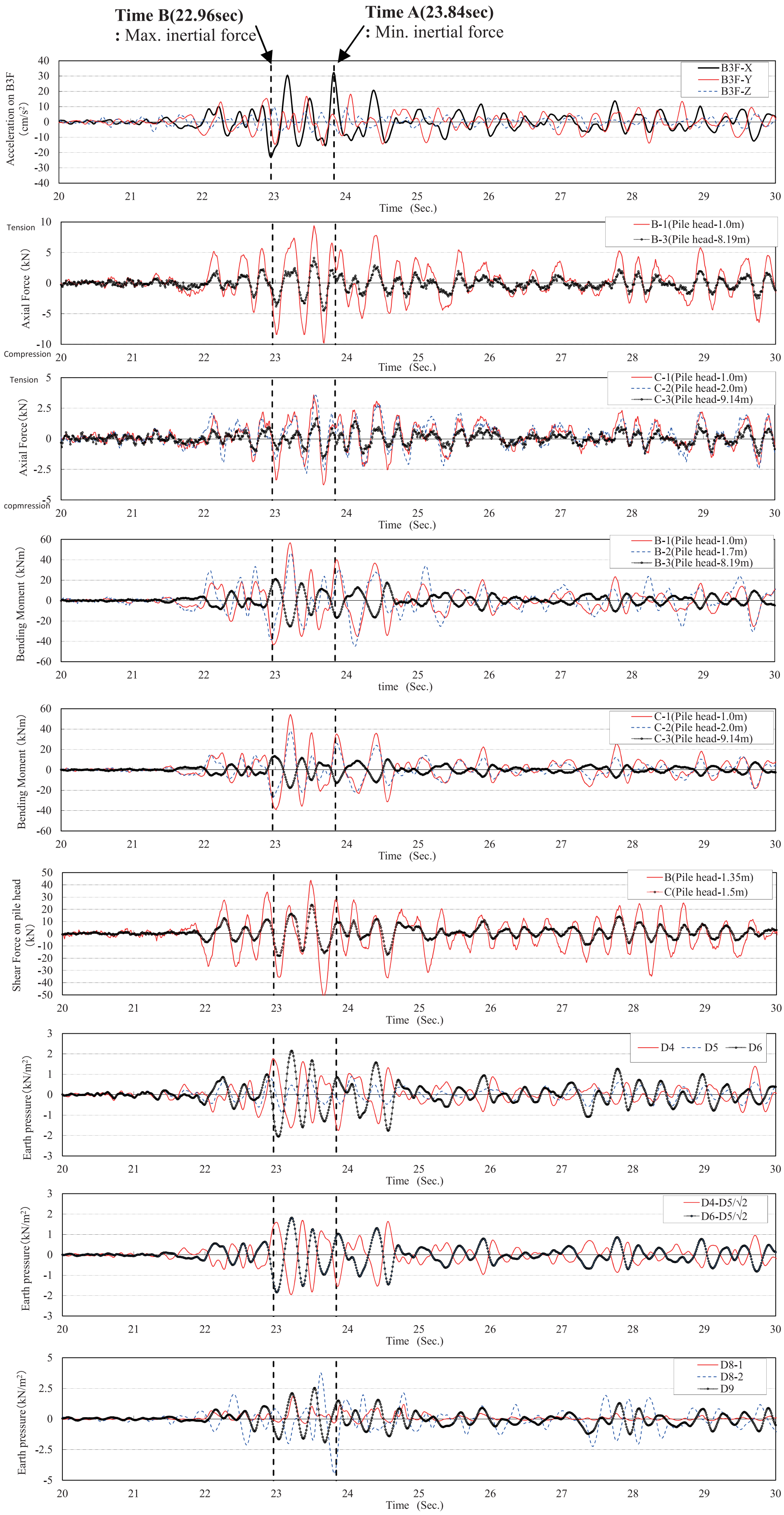
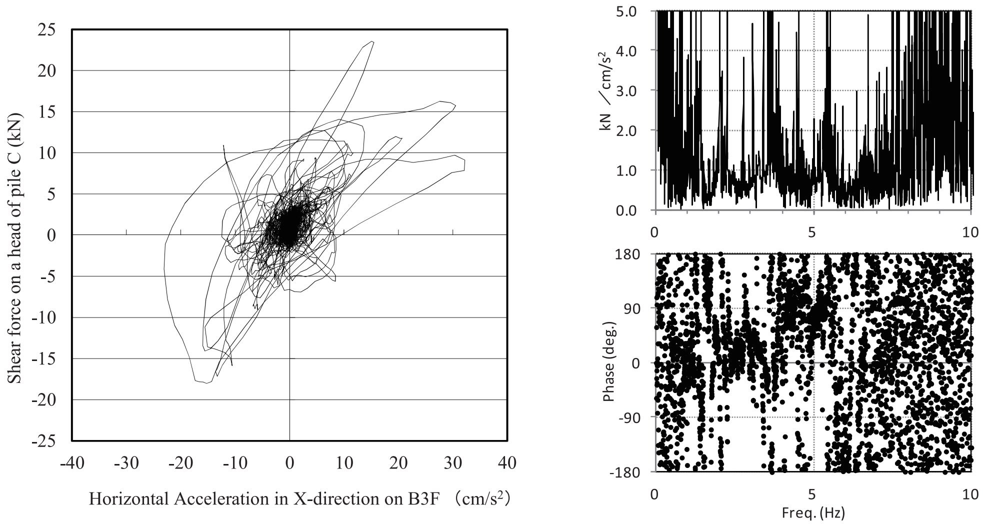
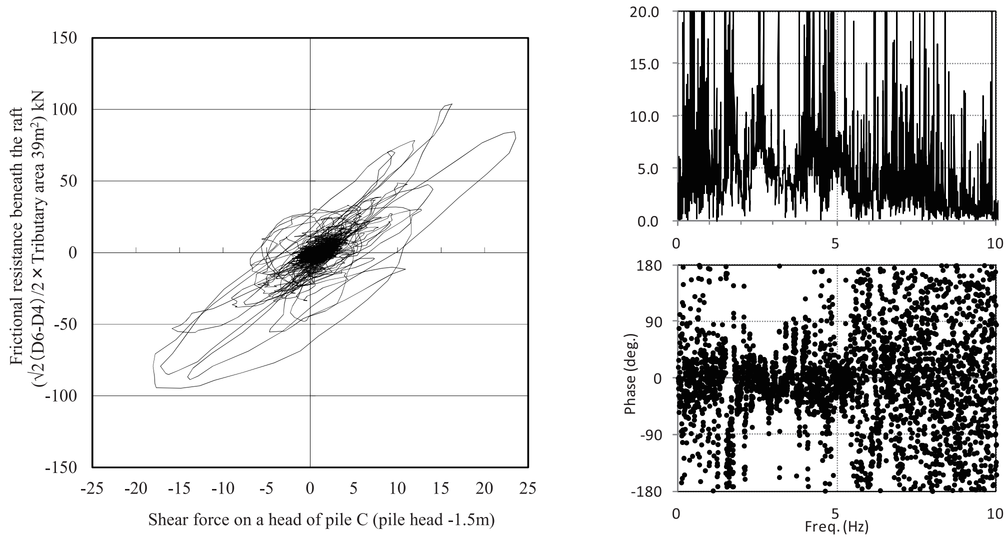


Fig. 8 Time histories of accelerations, sectional forces and earth pressures (April 16, 2011)



(a) Hysteresis curve (a) Spectral ratio

Fig. 9 Relationship between horizontal acceleration and shear force at pile head



(a) Hysteresis curve (b) Spectral ratio

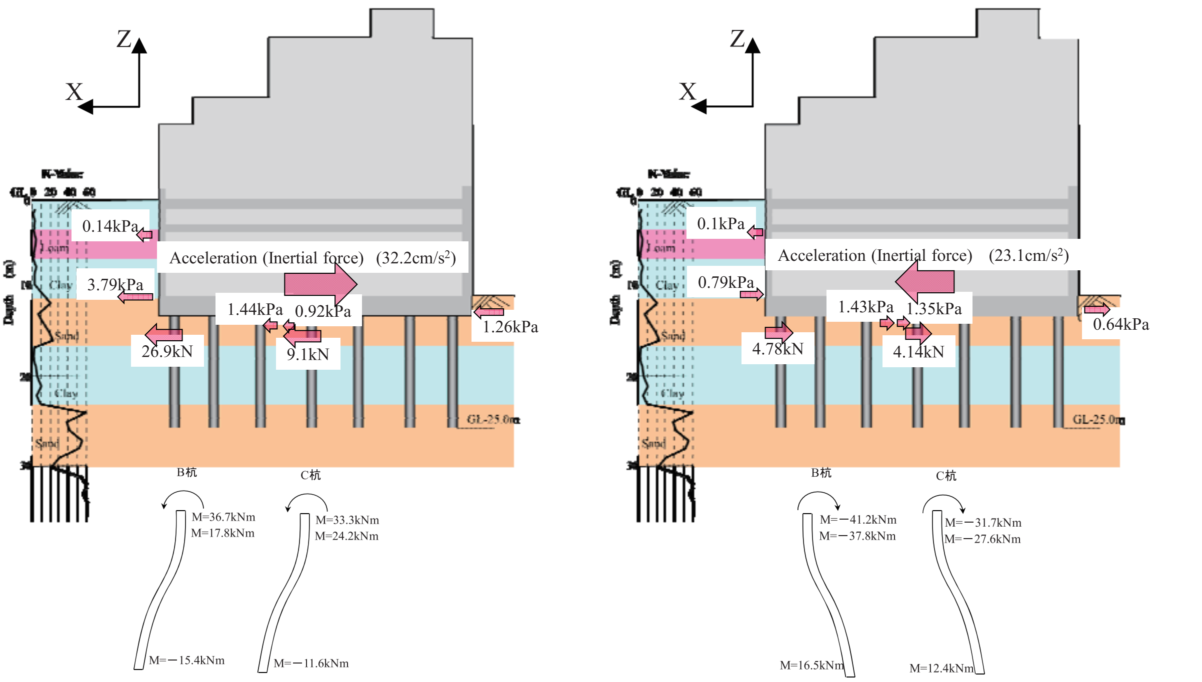
Fig. 10 Relationship between shear force of pile head and lateral resistance of raft

5.2 Estimation of Lateral Load Balance

Lateral load balances are shown in Fig. 11 when the inertial force of the building is maximum or minimum. The times A and B in Fig. 11 correspond to those shown in Fig. 8. These figures also show the measured bending moment of the piles and an image of deflection of the piles. The shear force at the pile head and the frictional resistance beneath the raft was working against the inertial force of the building. The embedded side walls were also working against the inertial force.

6 CONCLUSUIONS

Seismic observations on the piled raft foundation subjected to unsymmetrical earth pressure were performed since after the 2011 off the Pacific Coast of Tohoku Earthquake. Accelerations of the building, dynamic sectional forces of piles and dynamic earth pressures on both sides of the embedded foundation and beneath the raft were observed at maximum acceleration of 0.322 m/s^2. 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 also working against the inertial force.



(a) At minimum fo inerta force (-X direction), TimeA (b) At maximum fo inerta force (+X direction), Time B

Fig. 11 Lateral load balance

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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