# Settlement and Load Sharing Behavior of Piled Raft Foundations Based on Long-Term Monitoring
## 長期挙動観測に基づくパイルド・ラフト基礎の沈下と荷重分担挙動

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## Summary

This paper presents behavior of settlement and load sharing between piles and raft based on the long-term monitoring of eleven structures. For the three out of the eleven structures, foundation behavior during the 2011 off the Pacific coast of Tohoku Earthquake was successfully monitored. No significant changes in foundation settlement or load sharing were observed after the earthquake in these three buildings, and the foundation settlements were 18 to 27 mm and the ratio of the load carried by the piles to the effective load generally decreased as the pile spacing was increased while the ratio of the load carried by the piles varied from 0.4 to 0.9.

Keywords: piled raft foundation, settlement, load sharing, monitoring, seismic loading

## 梗 概

本文は，パイルド・ラフト基礎の沈下および杭とラフトの荷重分担性状について，11件の建物の長期挙動観測結果に基づき述べたものである。このうち3件の建物については，観測期間中に発生した2011年東北地方太平洋沖地震前後の基礎の挙動が観測されている。結論として，地震動による基礎の沈下量と荷重分担の変化は小さいこと，パイルド・ラフト基礎の沈下量は18～27mmであること，建物の有効荷重に対する杭の荷重分担率は0.4～0.9であるが杭間隔が増加すると減少する傾向を示すことが判明した。

キーワード：パイルド・ラフト基礎，沈下，荷重分担，挙動観測，地震荷重

## 1 INTRODUCTION

In recent years, there has been an increasing recognition that the use of piles to reduce raft settlement can lead to considerable economic savings without compromising the safety and the performance of the foundations (Poulos, 2001). Piled raft foundations have been used in Japan for many buildings and the effectiveness of piled rafts in reducing average and differential settements has been confirmed not only on favorable ground conditions as shown by Katzenbach et al. (2000) and Mandolini et al. (2005), but also on unfavorable ground conditions with ground improvement techniques (Yamashita et al., 2011a; Yamashita et al., 2011b; Yamashita, 2012). It has become necessary to develop more reliable seismic design methods for piled raft foundations, particularly in highly seismic areas such as Japan. However, only a few case histories on monitoring seismic soil-pile-structure interaction behavior exist (Mendoza et al., 2000).

This paper presents behavior of settlement and load sharing between piles and raft based on the long-term monitoring of eleven structures. For the three of the eleven structures, foundation behavior subjected to seismic motion during the 2011 off the Pacific coast of Tohoku Earthquake was successfully monitored. First, performance of the piled rafts supporting the three structures during the earthquake is presented, and the effects of the strong seismic motion on the foundation settlement and the load sharing between the piles and the raft are discussed. Next, based on the monitoring results, general aspects of the foundation settlement and the load sharing between the piles and the raft are discussed.
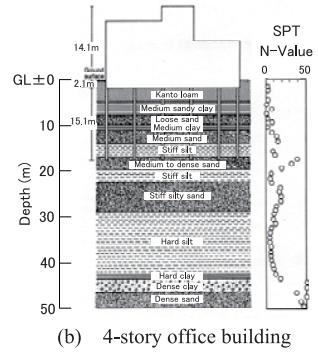
＊1 Executive Manager, Research & Development Institute, Dr. Eng. 技術研究所 専門役 博士（工学）
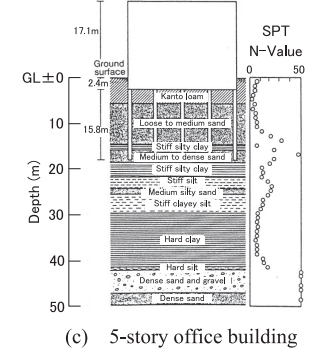＊2 Chief Researcher, Research & Development Institute, Dr. Eng. 技術研究所 主任研究員 博士（工学）
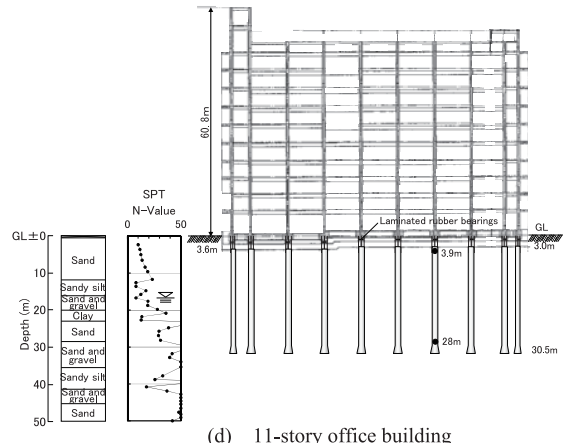＊3 Researcher, Research & Development Institute 技術研究所 研究員
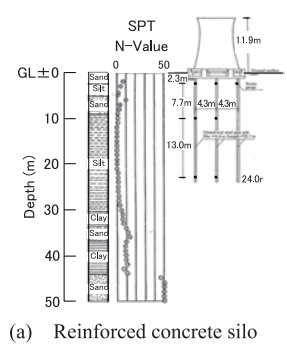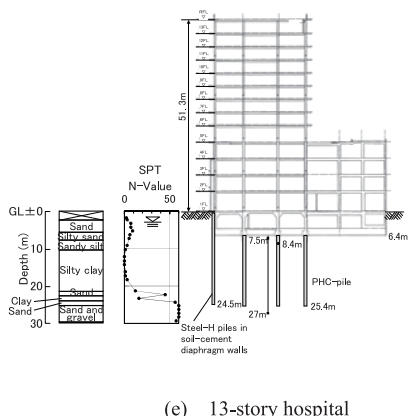
(a) Reinforced concrete silo
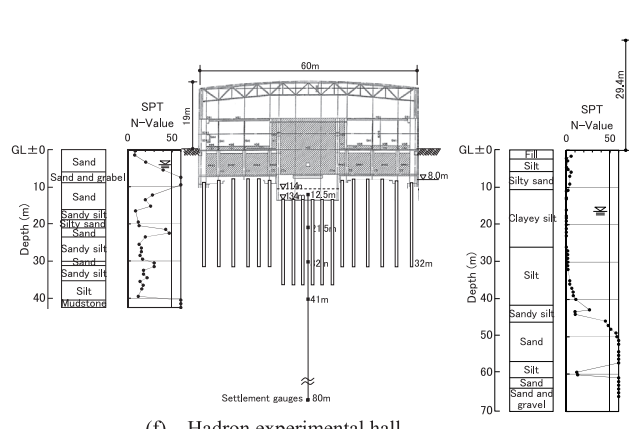
(b) 4-story office building
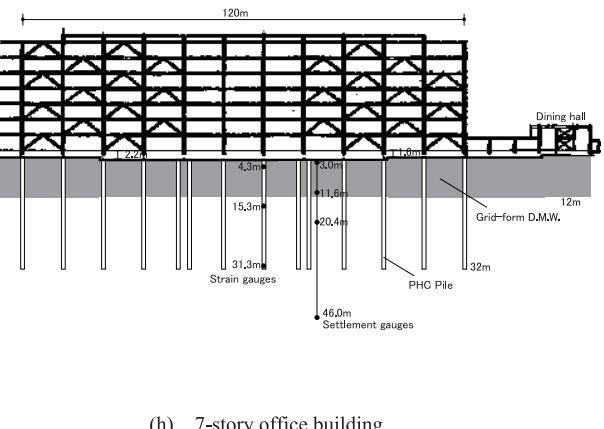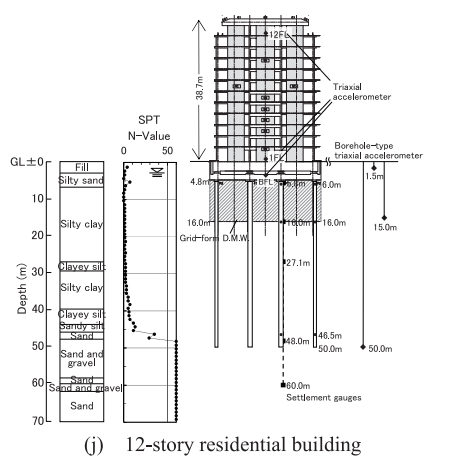
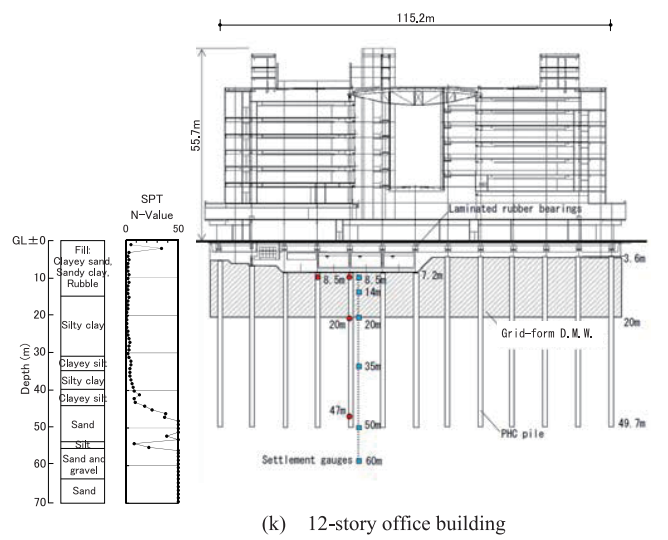(c) 5-story office building

(d) 11-story office building

(e) 13-story hospital

(f) Hadron experimental hall

(h) 7-story office building

(j) 12-story residential building
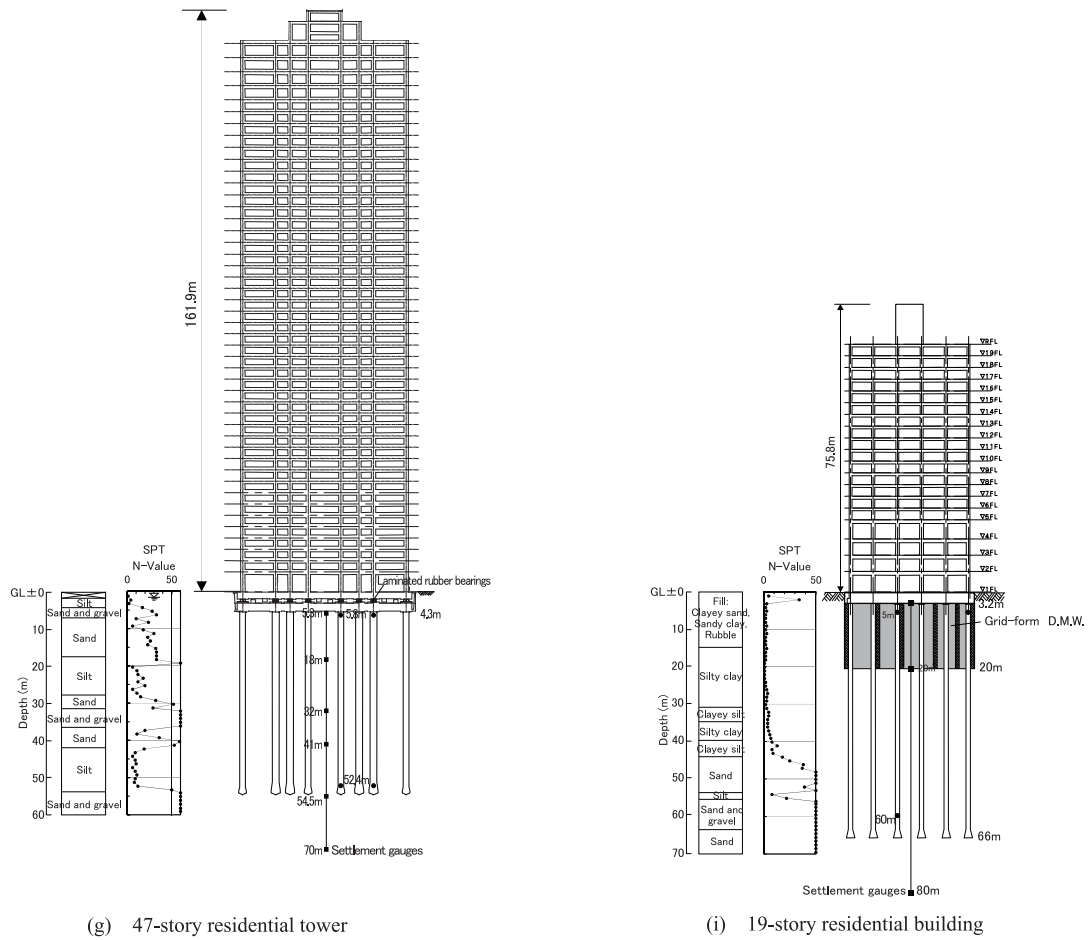
(k) 12-story office building

(g) 47-story residential tower      (i) 19-story residential building

Fig. 1   Schematics of eleven structures with soil profiles

Table 1   General description of structures and foundations

| No. | Structure | Site | Construction period | Maximum height (m) | Average contact pressure (kPa) | Depth of foundation (m) | Depth of groundwater table (m) | Piles | | | | Ref. No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Number | Length (m) | Diameter (m) | Pile type | |
| a | Reinforced concrete silo | Tokyo | 1983-84 | 11.9 | 74 | 1.3 | 2.0 | 5 | 22.7 | 0.40 | Steel-pipe pile | 9) |
| b | 4-story office building | Saitama | 1986-87 | 14.1 | 61 | 2.1 | 4.0 | 16 | 15.1 | 0.25×0.25-0.40×0.40 | Steel-H pile | 10) |
| c | 5-story office building | Saitama | 1992-93 | 17.1 | 84 | 2.4 | 5.0 | 20 | 14.6−15.8 | 0.30×0.30-0.41×0.41 | Steel-H pile | 11) |
| d | 11-story office building | Aichi | 2004-05 | 60.8 | 145 | 3.0, 3.6 | 17.0 | 40 | 27.5, 26.9 | 1.1/1.4*-1.5/1.8* | Cast-in-place concrete pile | 4) |
| e | 13-story hospital | Osaka | 2004-05 | 51.3 | 169 | 6.4 | 2.5 | 17 | 19.0 | 0.8-1.0 | PHC pile (pre-boring) | 4) |
| f | Hadron experimental hall | Ibaraki | 2005-07 | 19.0 | 259−442 | 8.0−13.4 | 4.0 | 371 | 22.0−25.7 | 0.6-0.8 | PHC pile (pre-boring) | 4),12) |
| g | 47-story residential tower | Aichi | 2006-09 | 161.9 | 600 | 4.3 | 2.5 | 36 | 50.2 | 1.5-1.9/2.9* | Cast-in-place concrete pile | 4) |
| h | 7-story office building | Tokyo | 2003-04 | 29.4 | 100 | 1.6, 2.2 | 1.5 | 70 | 29.8, 30.4 | 0.6-0.9 | PHC pile (pre-boring) | 5) |
| i | 19-story residential building | Kagoshima | 2005-06 | 75.8 | 257 | 3.2 | 3.0 | 28 | 62.8 | 1.2/1.8*, 1.3/2.2* | Cast-in-place concrete pile | 4) |
| j | 12-story residential building | Tokyo | 2007-08 | 38.7 | 199 | 4.8 | 1.8 | 16 | 45.0 | 0.8-1.2 | PHC pile (pre-boring) | 5), 13), 15) |
| k | 12-story office building | Tokyo | 2009-11 | 55.7 | 187 | 3.6-7.2 | 3.0 | 180 | 42.5−46.1 | 0.6-1.2 | PHC pile (pre-boring) | 14), 15) |

＊ Diameter of enlarged base

## 2 CASE HISTORIES

Figure 1 shows schematics of the eleven structures with the soil profiles. Table 1 presents a general description of the structures and foundations. The soil conditions and the foundation design as well as the instrumentation for monitoring were described in detail in the previous papers listed in Table 1. In the 1980s and 1990s, piled raft foundations were applied mainly to small-scale structures such as those shown in Figs. 1(a) to 1(c) where field measurements on the foundation settlement and the axial loads of the piles, the contact pressure beneath the raft were performed to investigate the effectiveness of piled rafts (Kakurai et al., 1987; Yamashita and Kakurai, 1991; Yamashita et al., 1994). These foundations may be called 'piled rafts of the first generation in Japan'.

Piled raft foundations have been used for the relatively large structures such as those shown in Figs. 1(d) to 1(k), including a tall building in excess of 150 m in height, since a basic design framework has been established in the early 2000s (Yamashita, 2012). The foundation design of the eight piled rafts was based on the common design method (Yamashita et al., 1998; Yamashita et al., 2011a). In addition, for the four structures on soft ground shown in Figs. 1(h) to 1(k), piled rafts with grid-form deep mixing walls were used to prevent soil liquefaction beneath the raft due to large earthquakes (Yamashita et al., 2011b; Yamashita et al., 2012; Yamashita et al., 2013a; Yamashita et al., 2013b). To confirm the validity of the foundation design of the relatively large structures, field monitoring were performed from the beginning of the construction to 17 to 102 months after the end of the construction (E.O.C.).

On March 11, 2011, the 2011 off the Pacific coast of Tohoku Earthquake, with an estimated magnitude of $M_w=$ 9.0 on the Moment Magnitude Scale, struck East Japan. As for the three structures, i.e., the hadron experimental hall, the 12-story residential building and the 12-story office building, the results of monitoring before and after the earthquake were successfully obtained.

## 3 EFFECT OF THE EARTHQUAKE

### 3.1 Seismic Ground Motion

Figure 2 shows the peak ground acceleration map derived from the strong motion records of K-NET and
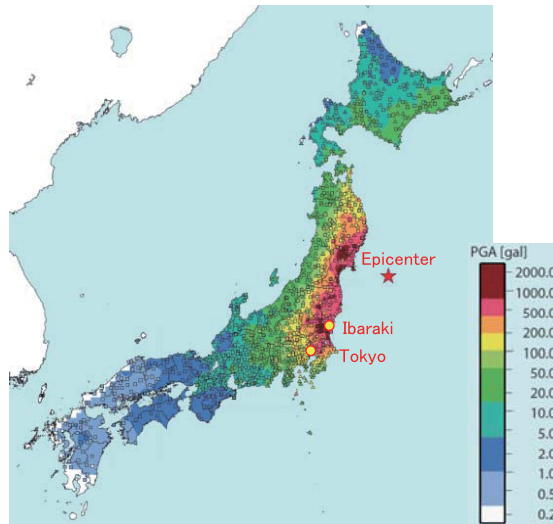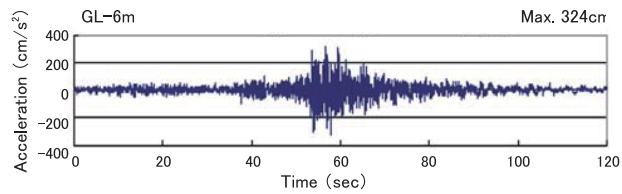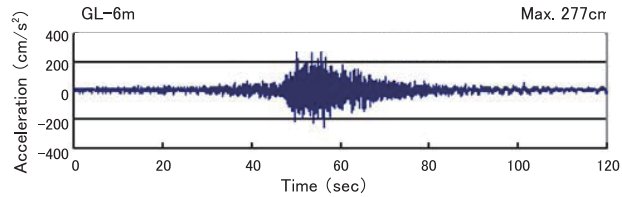


Fig. 2 PGA map derived from strong motion records (Kunugi et al., 2012)[16]



(a) Horizontal direction



(b) Vertical direction

Fig. 3 Time histories of accelerations at Tokai (Hashimura et al., 2011)[17]
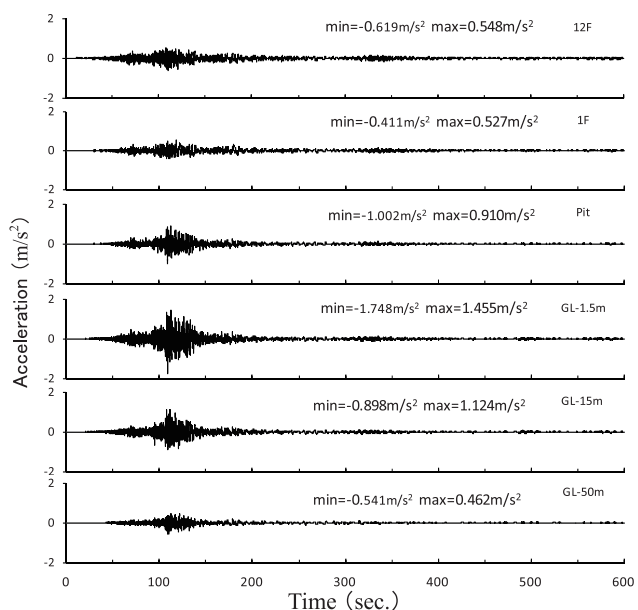


Fig. 4 Time histories of EW accelerations at Toyo in Tokyo

KiK-net (Kunugi et al., 2012). The hadron experimental hall is located in Ibaraki about 270 km from the epicentre. Figure 3 shows the time histories of the horizontal and vertical ground accelerations recorded at the strong motion station 0.4 km south from the hadron experimental hall (Hashimura et al., 2011). The peak horizontal and vertical ground accelerations at a depth of 6 m below the ground surface were 3.24 $m/s^2$ and 2.77 $m/s^2$, respectively. The 12-story residential building and the 12-story office building are located in Tokyo about 380 km from the epicentre. Figure 4 shows the time histories of the horizontal ground accelerations recorded at the site of the 12-story residential building. The peak horizontal and vertical ground accelerations near the ground surface were 1.75 $m/s^2$ and 0.75 $m/s^2$, respectively (Yamashita et al., 2012).

## 3.2　Hadron Experimental Hall

The hadron experimental hall shown in Fig. 1(f) is located at J-PARC (Japan Proton Accelerator Research Complex) in Ibaraki Prefecture. The soil conditions, the foundation design and the instrumentation, together with the results of the long-term monitoring on the settlement and the load sharing, were described in the previous paper (Yamashita et al., 2014).

The average pressure over the raft in design was 259 kPa in the experimental line, 350 kPa in the beam line and 442 kPa in the beam dump. The live loads were relatively large, 67 to 84% of the total load, because a large amount of iron and concrete shielding blocks were to be set up after E.O.C. In order to reduce the settlement of the raft foundation due to the compression of the cohesive soil layers below the depth of 23 m, a piled raft foundation consisting of 371 PHC (pre-tensioned spun high-strength concrete) piles, 22.0 to 25.5 m-long and 0.60 to 0.80 m in diameter, was employed. The piles were constructed by inserting a couple of pile segment into a pre-augered borehole filled with mixed-in-place soil cement. Figure 5 shows the foundation plan with a layout of the piles with the locations of the monitoring devices.

Figure 6 shows the measured vertical ground displacements near the centre of the raft relative to a depth of 80 m. The ground displacement at a depth of 12.5 m was approximately equal to the foundation settlement. The foundation settlement was 12.4 mm at E.O.C. Thereafter, the settlement incr eased due to the setting up of the shielding blocks. The foundation settleme nt measured just before the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011 was 20.7 mm. On April 8, 2011, 28 days
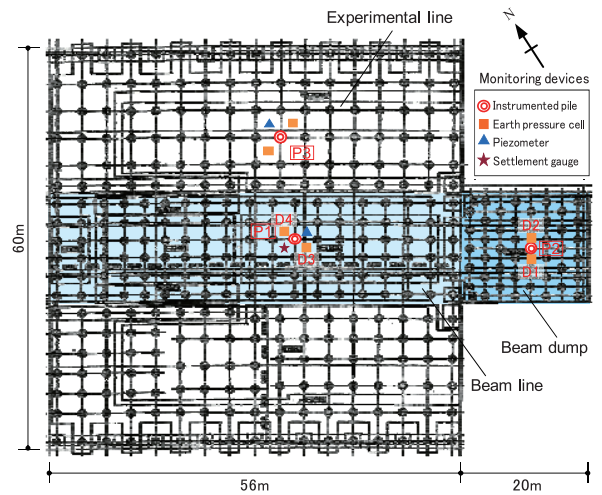


Fig. 5　Foundation plan with locations of monitoring devices
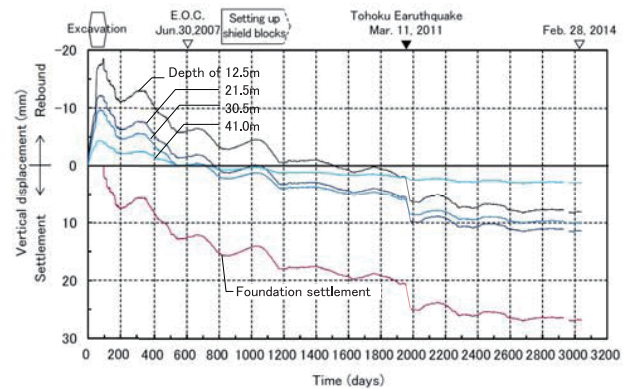


Fig. 6　Measured vertical ground displacements in beam line
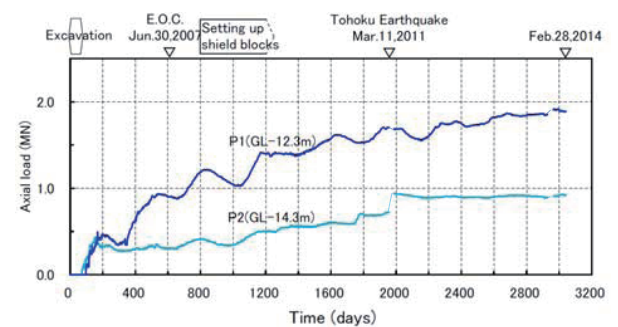


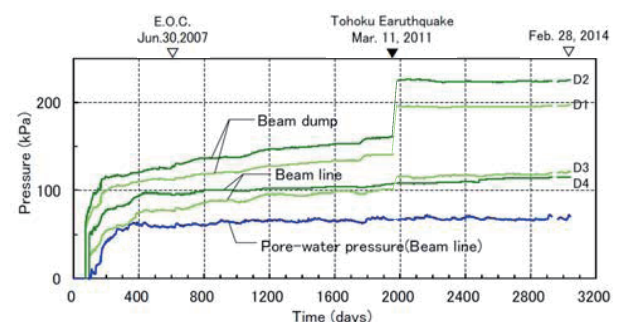Fig. 7　Measured axial loads at pile head



Fig. 8　Measured contact pressure with pore-water pressure

after the earthquake, the measured foundation settlement was 24.8 mm which was increased by 4.1 mm from the pre-earthquake value. Since the maximum vertical ground acceleration was relatively large, approximately 2.0 m/s$^2$ as shown in Fig. 3(b), it is likely that the increase in the ground settlement was caused by the vertical cyclic loading, as well as the rotational moment, from the superstructure. After the earthquake, a part of the shielding blocks was removed to align experimental devices in the beam line. This caused the decrease in the foundation settlement and that in the total load as shown in Figs. 6 and 9(a), respectively. The shielding blocks were set up again and the foundation settlement increased. Thereafter, the foundation settlement was stable and reached 26.7 mm 36 months after the earthquake (February 28, 2014).

Figure 7 shows the measured pile-head load of Piles P1 and P2 versus time. Figure 8 shows the measured contact pressure together with the pore-water pressure beneath the raft in the beam line and the measured contact pressure in the beam dump.

Figure 9 shows the time-dependent load sharing among the piles, the soil and the buoyancy in the tributary area of Piles P1 and P2. As shown in Figs. 7 and 9, the axial loads of Pile P1 decreased very slightly and the effective raft load increased slightly after the earthquake, while the axial load of Pile P2 at pile head increased 30% and the effective raft load increased 39% after the earthquake. Here, the effective raft load is raft load minus buoyancy where the raft load means the sum of the total load carried by the soil. The increase in the loads of both the pile and the raft in the beam dump seemed to be caused by the loss of the vertical frictional resistance on the basement walls due to the subsidence of the backfill sand induced by the strong seismic motion. As a result, a part of the structure load, which had been supported by the frictional resistance, was transferred to the bottom of the raft and distributed to the soil beneath the raft and the piles. Figure 10 shows the ratio of the load carried by the piles to the effective load in the tributary area of Piles P1 and P2. The ratio of the load carried by the Pile P1 decreased only slightly from 0.85 to 0.82, while that carried by Pile P2 decreased slightly from 0.67 to 0.57 28 days after the earthquake. This indicates that a small amount of load transfer from the piles to the soil occurred due to the strong seismic motion. Thereafter, the load sharing between the piles and the raft was found to be quite stable.

## 3.3 Twelve-Story Residential Building

The 12-story residential building shown in Fig. 1(j) is a



（a）Beam line (Pile P1)
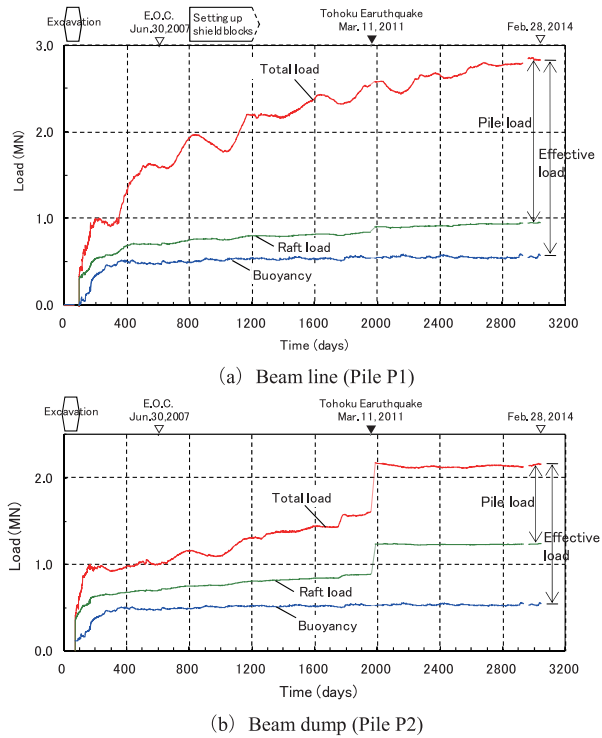


（b）Beam dump (Pile P2)

Fig. 9    Load sharing between piles and raft
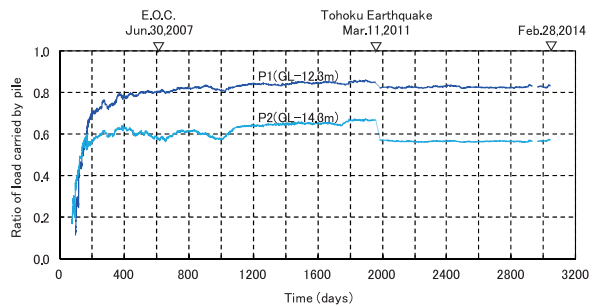


Fig. 10    Ratio of pile load to effective load in tributary area
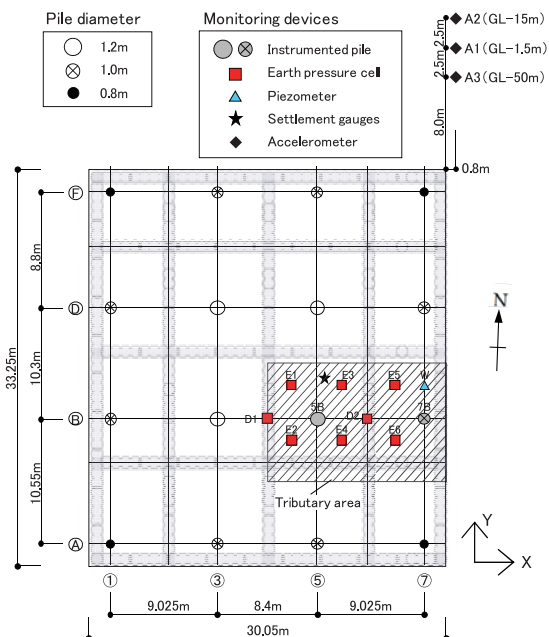


Fig. 11    Foundation plan with locations of monitoring devices

reinforced concrete structure with a base isolation system of laminated rubber bearings. The building is located in Tokyo. The soil conditions, the foundation design and the instrumentation, as well as the seismic response of the soil-foundation-structure system, were described in the previous paper (Yamashita et al., 2011b; Yamashita et al., 2012). In addition, the monitoring results were updated from those in the previous paper (Yamashita et al., 2013b).

The total load was 198.8 MN. The average contact pressure over the raft was 199 kPa. To improve the bearing capacity of the silty soil beneath the raft, as well as to cope with the liquefiable loose silty sand between depths of 3 and 7 m below the ground surface, the grid-form deep mixing walls were constructed to a depth of 16 m with the bottom being embedded in the lower stiffer silty clay. Furthermore, to reduce the settlement to acceptable levels, sixteen 45-m-long PHC piles, 0.8 to 1.2 m in diameter, were used. The pile toes reached the very dense sand-and-gravel layer sufficiently well enough to ensure the toe resistance as well as the frictional resistance. The piles were constructed by inserting a set of pile segments into a pre-augered borehole filled with mixed-in-place soil cement. Figure 11 shows the foundation plan with the locations of the monitoring devices.

Figure 12 shows the measured vertical ground displacements near the center of the raft. The vertical ground displacement at a depth of 5.8 m, which was initialised after the immediate settlement due to the casting of mat slab, was approximately equal to settlement of "piled raft foundation". The foundation settlement reached 14.3 mm at E.O.C. The foundation settlement reached 17.3 mm on March 10, 2011, just before the 2011 off the Pacific coast of Tohoku Earthquake. After the earthquake, the foundation settlement increased by 0.3 mm from the pre-
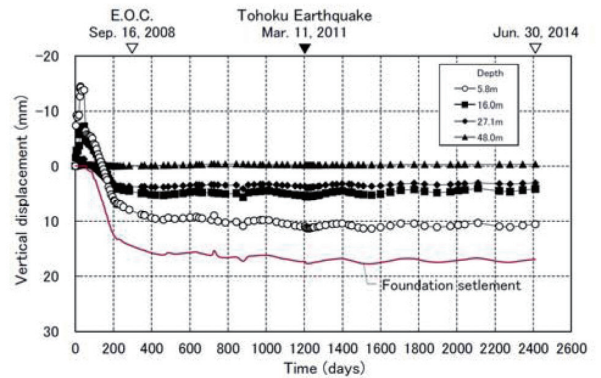


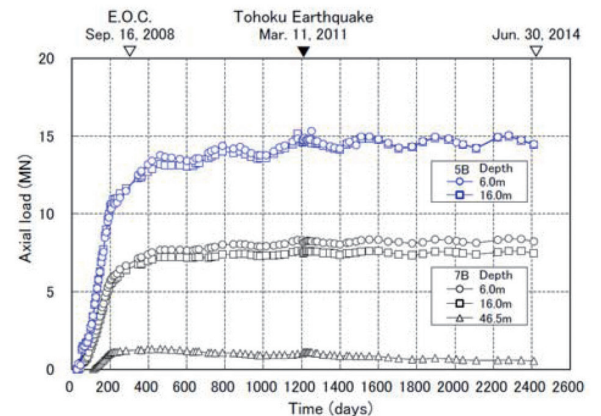Fig. 12    Measured vertical ground displacements below raft



Fig. 13    Measured axial loads of piles 5B and 7B
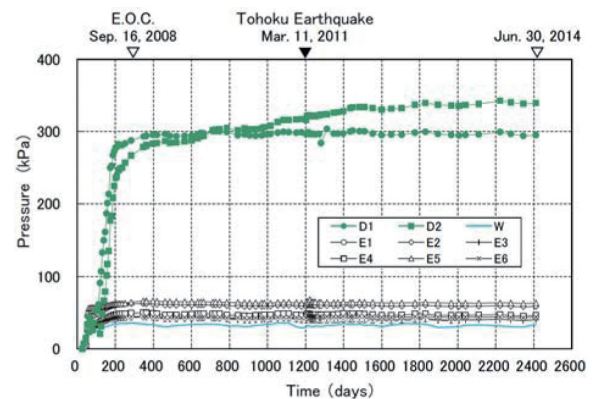


Fig. 14    Measured contact pressure with pore-water pressure
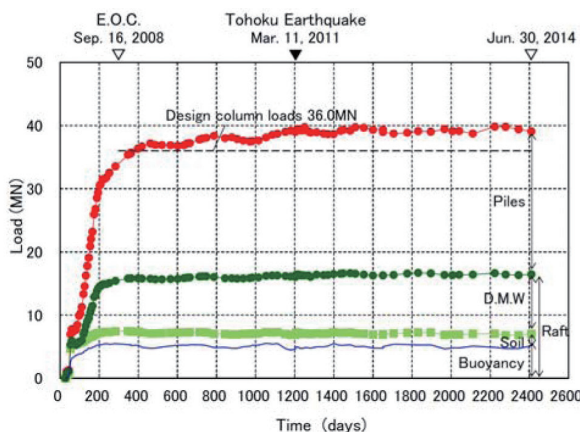


Fig. 15    Load sharing among piles, deep mixing walls and
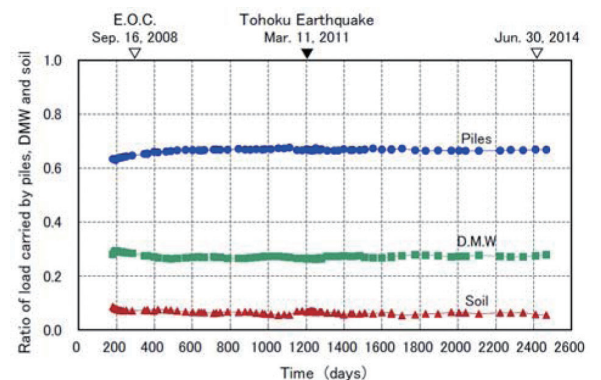soil in tributary area



Fig. 16    Load sharing of effective load among piles, deep mixing
walls and soil in tributary area

Table 2 Load sharing among piles, deep mixing walls and soil

|  | Sep. 16, 2008[*1] | Mar. 10, 2011[*2] | Mar. 11, 2011[*3] | Mar. 15, 2011 | Apr.10,2012 to Jun.30,2014 |
|---|---|---|---|---|---|
| Ratio of load carried by piles | 0.646 (0.540) | 0.669 (0.589) | 0.660 (0.580) | 0.667 (0.582) | 0.663-0.672 (0.574-0.588) |
| Ratio of effective load carried by D.M.W. | 0.283 | 0.264 | 0.266 | 0.266 | 0.268-0.278 |
| Ratio of effective load carried by soil | 0.071 | 0.067 | 0.074 | 0.067 | 0.053-0.065 |

Values in parentheses are ratios of pile load to total load  　＊1 End of construction  　＊2 Pre-earthquake  　＊3 Near end of the earthquake (600s after start of event)

earthquake value to 17.6 mm on March 15, 2011. Therefore, no significant change in foundation settlement was observed after the earthquake. Thereafter, the foundation settlements varied from 16.7 to 17.8 mm and were found to be quite stable.

Figure 13 shows the development of the measured axial loads of piles 5B and 7B. The axial load at the pile head of pile 7B decreased very slightly just after the earthquake, while that of pile 5B changed little. Figure 14 shows the development of the measured contact pressure between the raft and the soil and that between the raft and the deep mixing walls (DMW), together with the pore-water pressure beneath the raft. The contact pressure between the raft and the DMW near the periphery (D2) increased slightly from the pre-earthquake value, while the contact pressure in the inner part (D1) increased very slightly.

Figure 15 shows the time-dependent load sharing among the piles, the DMW, the soil and the buoyancy in the tributary area of columns 5B and 7B. The sum of the measured pile-head loads and the raft load in the tributary area after E.O.C. was 35.4-39.8 MN. Here, the raft load means the sum of the total load carried by the DMW and that by the soil. The sum of the measured pile-head loads and the raft load in the tributary area roughly agreed with the sum of the design load for columns 5B and 7B of 36MN. Figure 16 shows the load sharing among the piles, the DMW and the soil in the tributary area versus time. The values of the ratio of the load carried by each component to the effective load after E.O.C. are shown in Table 2. The ratio of the load carried by the piles to the effective load was estimated to be 0.67 just before the earthquake. At that time, the ratio of the effective load carried by the DMW was estimated to be 0.26, while the ratio of the effective load carried by the soil was 0.07. During the earthquake, the ratio of the load carried by the piles decreased very slightly near the end of the event, and then increased close to the pre-earthquake value four days after the event. The ratio of the effective load carried by the soil increased only slightly from the pre-earthquake value near the end of the event, and then decreased to the pre-earthquake value four days after the event, while the ratio of the effective load carried by the DMW increased very slightly from the pre-earthquake value, and then changed little. This indicates that a very small amount of load transfer from the piles to both the soil and the DMW occurred during the earthquake, and then the load transfer from the soil to the piles occurred within four days after the earthquake. Thereafter, the load sharing among the piles, the DMW and the soil was quite stable.

## 3.4 Twelve-Story Office Building

The 12-story office building shown in Fig. 1(k) is a steel-framed structure with a base isolation system of laminated rubber bearings. The building is located in Tokyo, 0.3 km southeast from the 12-story residential building. The soil conditions, the foundation design and the instrumentation were described in detail in a previous paper (Yamashita et al., 2013a). In addition, the monitoring results were updated from those in the previous paper (Yamashita et al., 2013b).

The average contact pressure over the raft was 187 kPa. To improve bearing capacity of the raft, as well as to cope with
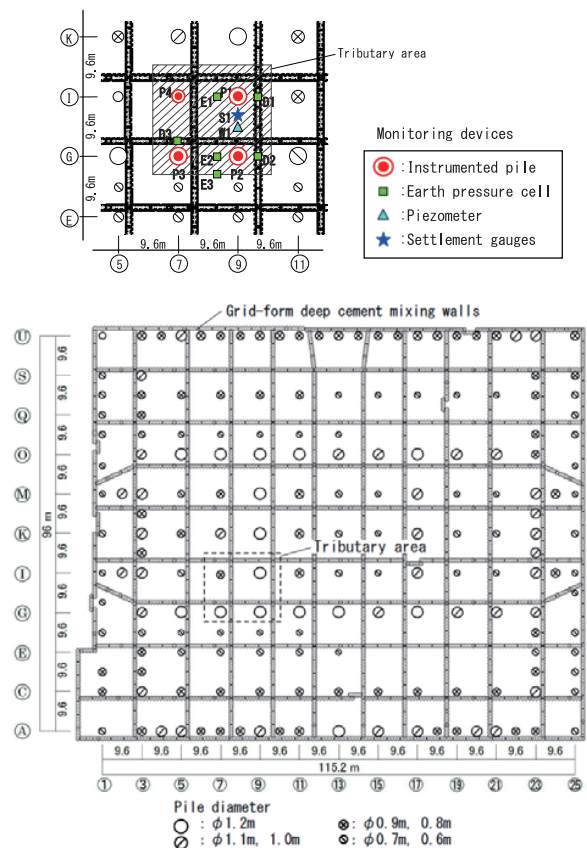


Fig. 17 Foundation plan with locations of monitoring devices

the liquefiable loose clayey sand between depths of 5 to 15 m below the ground surface, the grid-form deep mixing walls were constructed extending to the depth of 20 m with the bottom being embedded in the silty clay with undrained shear strength of 100 kPa or higher. Furthermore, to reduce the settlement and the differential settlement to an acceptable level, 180 PHC piles of 0.6 to 1.2 m in diameter were used. The pile toes were embedded in the very dense sand below the depth of 44 m enough to ensure the toe resistance as well as the frictional resistance. The construction method of piles was same as that used for the 12-story residential building. Figure 17 shows the foundation plan with the locations of the monitoring devices.

Figure 18 shows the measured vertical ground displacements below the raft. The ground displacement at the depth of 8.5 m was approximately equal to the foundation settlement. The 2011 off the Pacific coast of Tohoku Earthquake hit the building site nine months before E.O.C. at which about 80 % of the total load of the structure acted on the foundation. The foundation settlement was 15.0 mm on March 1, 2011, ten days before the earthquake. After the earthquake, the foundation settlement increased by 0.8 mm from the pre-earthquake value to 15.8 mm on March 16, 2011. Considering the increase in settlement due to the increase in the construction load during March 1 to March 11, no significant change in foundation settlement was observed after the earthquake. The foundation settlement increased considerably just before E.O.C. due to the water pouring into the underground pits. Thereafter, the settlement became stable and reached 21.2 mm 32 months after E.O.C. (August 1, 2014). Figure 19 shows the measured axial loads of Piles P1-P4 versus time. After the earthquake, the pile-head loads of Piles P1, P2 and P3 decreased very slightly from the pre-earthquake, while the pile-head loads of Piles P4 increased a little. Here, it should be noted that there was the increase in construction load before the earthquake mentioned above.
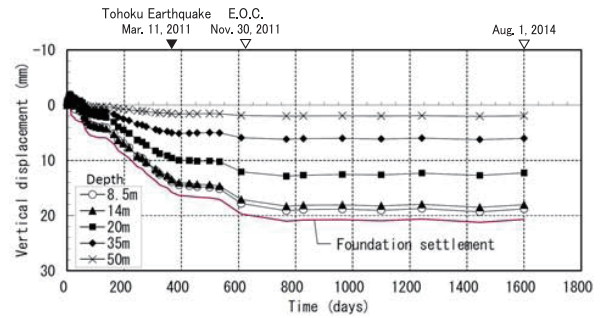


Fig. 18    Measured vertical ground displacements below raft



Fig. 19    Measured axial loads of piles
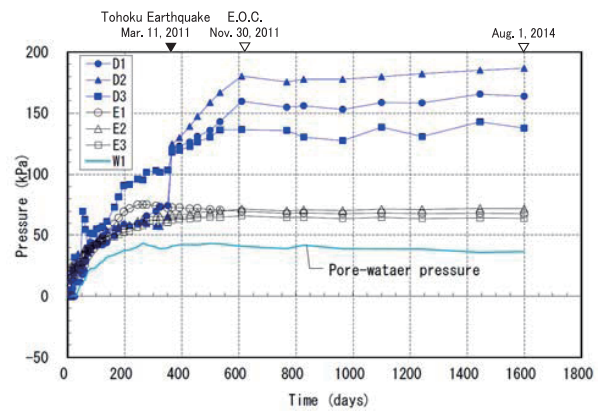


Fig. 20    Measured contact pressure with pore-water pressure

Thereafter, the axial loads increased considerably just before E.O.C. due to the water pouring in to the pits. Figure 2 0 shows the development of the measured contact pressure between the raft and the soil and that between the raft and the DMW, together with the pore-water pressure beneath the raft. Meanwhile, the contact pressure between the raft and the DMW increased markedly after the earthquake, while the contact pressure between the raft and the soil changed little. One reason for the increase in the contact pressure is supposed to be improvement of "weak contact" between the contact surface of the earth pressure cell and the top surface of the DMW due to the vertical cyclic loading from the raft during the earthquake.

Figure 21 shows the time-dependent load sharing among the piles, the soil, the DMW and the buoyancy in the tributary area of the instrumented piles. The sum of the measured pile-head loads and the raft load area varied from 61.3 to 64.1 MN after E.O.C., so that the sum of the measured pile-head loads and the raft load was generally consistent with the design load of 64.0 MN in the tributary area. Figure 22 shows the load sharing among the piles, the DMW and the soil in the tributary area versus time. The ratio of the load carried by the piles to the effective load was estimated to be 0.72 on March 1, 2011. At that time, the ratio of the effective load carried by the DMW was estimated to be 0.07, while the ratio of the effective load carried by the soil was 0.21. After the earthquake, the ratio of the load carried by the piles decreased slightly to 0.67 on March 16, 2011. The ratio
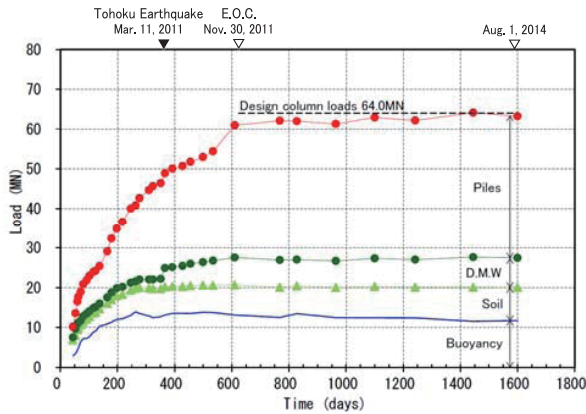
Fig. 21  Load sharing among piles, deep mixing walls and soil in tributary area
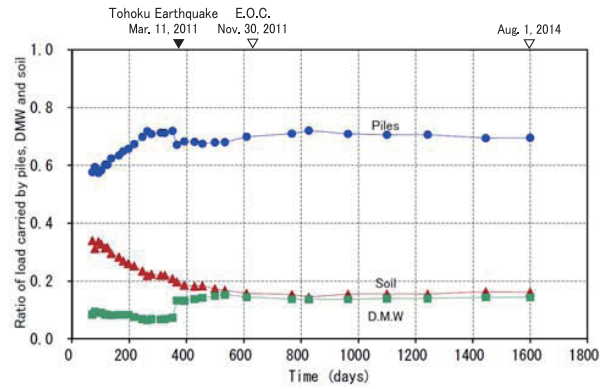
Fig. 22  Load sharing of effective load among piles, deep mixing walls and soil in tributary area

of the effective load carried by the soil decreased very slightly to 0.20, while the ratio of the effective load carried by the DMW increased significantly to 0.13. Thereafter, the ratio of the load carried by the piles to the effective load increased slightly to 0.7 0 and the ratio of the effective load carried by the DMW to the effective load increased only slightly just before E.O.C., while the ratio of the effective load carried by the soil decreased considerably from 0.21 to 0.17 in that term. This indicates that a small amount of load transfer from the soil to the piles occurred due to consolidation settlement of the soil.

After E.O.C., the load sharing among the piles, the DMW and the soil was quite stable. Namely, the ratio of the effective load carried by the piles to the effective load varied from 0.69 to 0.72, and the ratio of the effective load carried by the soil to the effective load varied from 0.14 to 0.16 while that carried by the DMW to the effective load was 0.14.

# 4  LONG-TERM SETTLEMENTS AND LOAD SHARING

## 4.1  Foundation Settlements

Figure 23 shows the foundation settlement versus elapsed time relationship for the seven structures, where line (e) to (k) refer to buildings (e) to (k) shown in Fig. 1. In these structures, the vertical ground displacements just below the rafts were successively measured from the beginning of the construction to 17 to 102 months after E.O.C. While the relationship for the six structures were originally shown in the previous paper (Yamashita, 2012), the data for the 12-story office building were newly added and those for the 13-story hospital were updated from those in the previous paper (Yamashita et al., 2011a). The measured settlements reached 18 to 27 mm at the end of the observation, while those at E.O.C. were 12 to 23 mm. The maximum value of 27 mm for the hadron experimental hall included the increase in settlement due to the strong seismic motion during the 2011 off the Pacific coast of Tohoku Earthquake. It was found that the measured foundation settlements at the end of the observation were within a limited range, and around 25 mm (one inch).

## 4.2  Load Sharing between Piles and Raft

Figure 24 shows the relationship between the ratio of the load carried by the piles to the effective load in the tributary area of
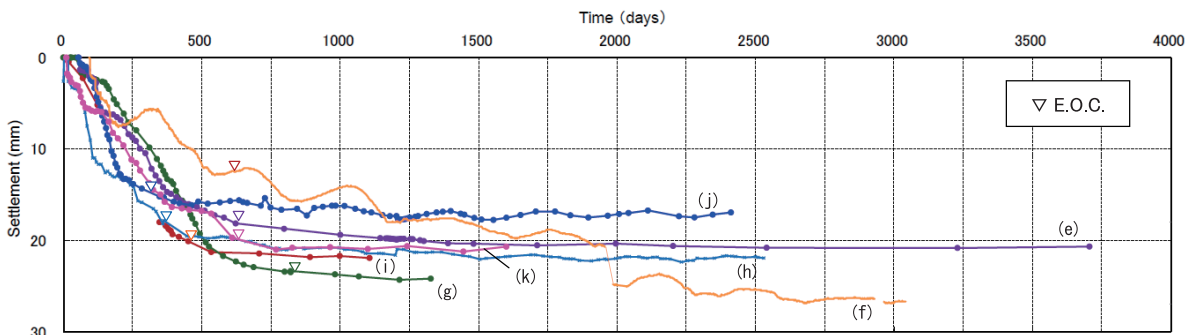


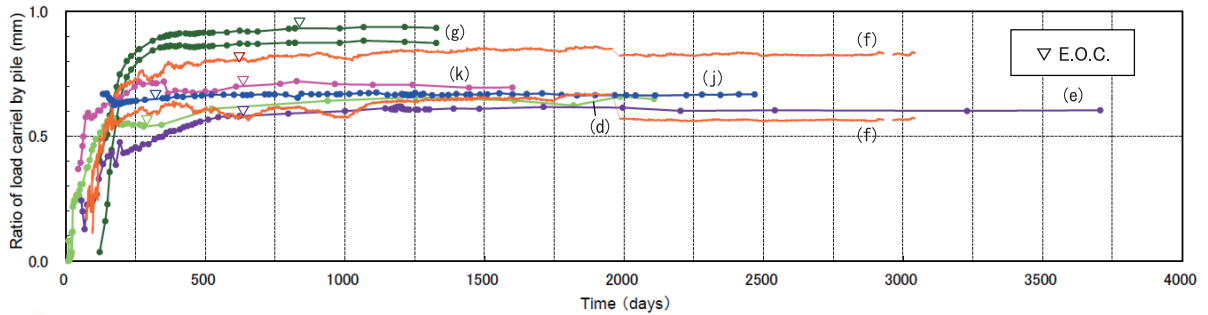Fig. 23  Measured foundation settlements vs. time

Fig. 24 Ratio of load carried by piles to effective load vs. time

the instrumented piles ($\alpha_p$') and the elapsed time, for the six structures shown in Figs. 1(d), 1(e), 1(f), 1(g), 1(j) and 1(k). The data for the 13-story hospital were updated from those in the previous paper (Yamashita et al., 2011a). The values of $\alpha p$' were found to be quite stable after E.O.C.

Figure 25 shows the values of $\alpha_p$' at or after the end of the construction versus the pile spacing ratio ($s/d$) for the eleven structures. Here, $s$ is the average center-to-center spacing between the instrumented pile and the adjacent piles and $d$ is the shaft diameter of the pile. While the $\alpha_p$' versus $s/d$ relationship for the ten structures was originally shown in the previous paper (Yamashita et al., 2011a), the data for the 12-story office building (k) were newly added and those for the 13-story hospital (e), the hadron experimental hall (f) and the 12-story residential building (j) were updated. In addition, for the hadron experimental hall in Ibaraki and the 12-story residential building in Tokyo, the values of $\alpha_p$' just before the 2011 off the Pacific coast of Tohoku Earthquake are also shown in Fig. 25. There was a little decrease in the values of $\alpha_p$' was observed for the former building, while little change was observed for the latter building after the strong seismic motion as mentioned in Chapter 3. While the value of $\alpha_p$' varied from 0.43 to 0.93, it was found that the value of $\alpha_p$' generally decreased as the pile spacing ratio was increased, as described in the previous paper (Yamashita et al., 2011a).



○ (a) 6 months after E.O.C.
□ (b) Average 1 year after E.O.C.
◇ (c) At E.O.C.
● (d) Average 22–60 months after E.O.C.
● (e) Average 25–102 months after E.O.C.
● (f) 80 months after E.O.C.
● (g) 17 months after E.O.C.
■ (h) 72 months after E.O.C.
■ (i) Average 8–22 months after E.O.C.
■ (j) 69 months after E.O.C.
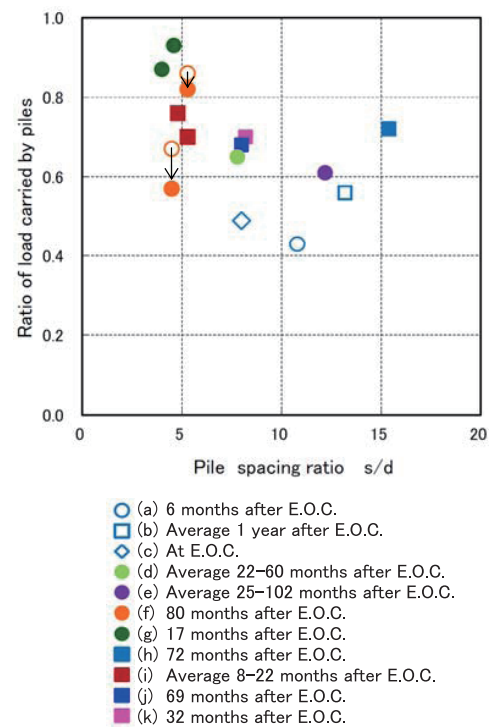■ (k) 32 months after E.O.C.

Fig. 25 Ratio of load carried by piles to effective load vs. pile spacing ratio

## 5 CONCLUSIONS

Through the investigation of the settlement and the load sharing behavior of piled raft foundations by monitoring the eleven structures, the following conclusions can be drawn:

1) As for the effect of the seismic motion during the 2011 off the Pacific coast of Tohoku Earthquake on the three structures, (f), (j), (k), the foundation settlement increased by 4 mm to 25 mm in the hadron experimental hall located in Ibaraki, while little changes in foundation settlements were observed in the 12-story residential building and the 12-story office building located in Tokyo. During the earthquake, a small amount of load transfer from the piles to the soil occurred in the hadron experimental hall and a very small amount of load transfer from the piles to both the soil and the D.M.W. occurred in the 12-story buildings. Thereafter, the load sharing between the piles and the soil (i.e., raft) was irreversivle in the hadron experimental hall, while the load transfer from the soil to the piles occurred in the 12-story buildings in relatively short period after the earthquake. As a result, no significant changes in foundation settlement or load sharing were observed after the earthquake.

2) For the seven structures, the measured foundation settlements reached 18 to 27 mm 17 to 102 months after E.O.C. The maximum settlement for the hadron experimental hall included the increment in settlement of 4 mm due to the strong seismic motion. It was found that the measured foundation settlements at the end of the observation were within a limited

range, about one inch.

3) The ratio of the load carried by the piles to the effective load in the tributary area of the instrumented piles ($\alpha_p{}'$), was found to be quite stable after E.O.C. While the value of $\alpha_p{}'$ at the end of the observation varied from 0.43 to 0.93, it was found that the value of $\alpha_p{}'$ generally decreased as the pile spacing ratio was increased, as described in the previous paper (Yamashita et al., 2011a).

## ACKNOWLEDGEMENTS

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