Settlement of piled raft subjected to strong seismic motion

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ABSTRACT

This paper presents settlement and load sharing behavior of a piled raft supporting a low-rise building subjected to strong seismic motion. On March 11, 2011, the 2011 off the Pacific coast of Tohoku Earthquake struck the building site. Based on the field monitoring results of the piled raft before and after the earthquake, it was found that the foundation settlement near the raft center was increased by 4.1 mm to 24.8 mm while the ratio of the load carried by the piles to the effective structure load was decreased slightly. A mechanism of the increase in settlement of the piled raft subjected to the strong seismic motion is discussed. Using a hysteretic load-unload-settlement curve derived from a rapid load pile testing and a settlement ratio obtained from the results of the pile testing and the field monitoring, the increment in settlement of the piled raft was estimated to be 3.8 mm which roughly agreed with the measured value.

Keywords: piled raft foundation, settlement, field monitoring, seismic motion, rapid load pile testing

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 for many buildings in Japan and the effectiveness in reducing overall and differential settlements has been confirmed not only on favorable ground conditions but also on unfavorable ground conditions with ground improvement techniques (Yamashita et al., 2011; Yamashita et al., 2012). It has become necessary to develop more reliable seismic design methods for piled raft foundations, particularly in highly seismic areas such as Japan. This paper presents settlement and load sharing behavior of a piled raft subjected to strong seismic motion during the 2011 off the Pacific coast of Tohoku Earthquake, focusing on the increment in settlement due to the earthquake.

2 BUILDINGS AND SOIL CONDITIONS

The hadron experimental hall is located at J-PARC (Japan Proton Accelerator Research Complex) in Ibaraki Prefecture (Yamashita et al., 2014). Figure 1 shows a schematic view of the structure with a soil profile. The subsoil consists of loose to dense sand to a depth of 6 m from the ground surface, underlain by diluvial very dense sand-and-gravel and medium to dense sand to a depth of 16 m. Between the depths of 16 to 23 m, lie medium sandy silt, loose silty sand and dense sand. Between the depths of 23 and about 40 m, lie stiff sandy silt and silt layers, underlain by a weathered sandy mudstone. The groundwater table appears about 4 m below the ground surface. Figure 2 shows the foundation plan with a layout of the piles. 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 the end of the construction.

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 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 9 to 15 m long segment into a pre-augered borehole filled with mixed-in-place soil cement. To confirm the validity of the foundation design, field monitoring on the settlement and the load sharing of piles and raft was performed. The locations of the monitoring devices are shown in Figure 2.

3 EFFECT OF EARTHQUAKE ON SETTLEMENT AND LOAD SHARING

3.1 The 2011 Tohoku Pacific Earthquake

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 on
March 11, 2011. The distance from the epicentre to the building site was about 270 km. 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. The peak horizontal and vertical ground accelerations at a depth of 6 m below the ground surface were 3.24 m/s² and 2.77 m/s², respectively (Hashimura et al., 2011).

3.2 Foundation settlements

Figure 4 shows the measured vertical ground displacements near the centre of the raft relative to a depth of 80 m. The ground displacement at the depth of 12.5 m was approximately equal to “foundation settlement” when it was initialized just before the casting of the foundation mats. The foundation settlement increased after the end of the construction (E.O.C.) due to the setting up of the shielding blocks and reached 20.7 mm on March 11, 2011, just before the earthquake.

After the earthquake (April 8, 2011), the foundation settlement was increased by 4.1 mm to 24.8 mm. It is likely that the increase in settlement of the ground was caused by the rotational and vertical cyclic loading from the superstructure, considering that the vertical ground acceleration of approximately 2.0 m/s² continued for about 10 s as shown in Figure 3(b).

The hadron experimental hall resumed operation in January 2012, after the alignment of the experimental devices. Thereafter, the foundation settlement increased only slightly due to the re-setting up of the shielding blocks to 26.7 mm three years after the earthquake.

3.3 Load sharing between piles and raft

Figure 5 shows the measured pile-head load of Piles P1 and P2. The pile-head load of both Piles P1 and P2...
increased considerably after E.O.C. due to the setting up of the shielding blocks. Figure 6 shows the measured contact pressure and the pore-water pressure beneath the raft near Piles P1 and P2. The contact pressure increased after E.O.C. while the measured pore-water pressure was almost constant, so that the effective pressure beneath the raft increased gradually.

Figure 7 shows the time-dependent load sharing among the piles, the soil and the buoyancy in the tributary area of Pile P1. Figure 8 shows that in the tributary area of Pile P2. The axial loads of Pile P1 decreased only slightly and the effective raft load (raft load minus buoyancy) increased slightly after the earthquake as shown in Figure 7. On the other hand, the axial load of Pile P2 at pile head increased 30% and the effective raft load increased 39% after the earthquake as shown in Figure 8. The increase in the loads of both the pile and the raft seemed to be caused by the loss of the vertical frictional resistance on the basement walls in the beam dump 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 9 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 and that carried by Pile P2 decreased slightly from 0.67 to 0.57 28 days after the earthquake. Thereafter, the ratios of the load carried by the piles to the effective

Fig. 4. Measured vertical ground displacements in beam line.

Fig. 5. Measured axial loads at pile head.

Fig. 6. Measured contact pressure and pore-water pressure

Fig. 7. Load sharing between pile and raft in Pile P1.

Fig. 8. Load sharing between pile and raft in Pile P2.

Fig. 9. Ratio of pile load to effective load in tributary area.
load were quite stable.

4 SETTLEMENT INDUCED BY EARTHQUAKE

4.1 Rapid load pile testing
To confirm the bearing capacity of the piles in design, a pile load test was conducted using a falling mass type rapid load pile testing technique shown in Photo 1 (Matsumoto et al., 2007). The test pile was 0.6 m in diameter and 28.8 m in embedded length, as shown in Figure 1. Although a depth of pile toe of the test pile was 5.0 m less than that of the instrumented pile in the beam line (Pile P1), the embedded length of the test pile was 8.2 m larger than that of Pile P1. The load cycles of the rapid load pile testing are shown in Table 1. The hammer mass was 35 tons and the pile loading consisted of 16 cycles. The load signals on the pile top was measured by a load cell, and the vertical displacement and acceleration of the pile head were measured by an optical displacement transducer and an accelerometer, respectively. The residual settlement at the pile head after each load cycle was measured by an optical level.

Figure 10 shows the load signals at the pile head. Figure 11 shows the load-settlement curves recorded in each load cycle, together with the equivalent static load-settlement behavior which was converted using the unloading point method (Middendorp et al., 1992). Furthermore, the equivalent static load-settlement curve was obtained assuming that the equivalent static load-settlement behavior of the 1st to 14th cycle was approximated by a hyperbolic.

4.2 Mechanism of increase in settlement
A mechanism of the increase in settlement of the piled raft due to the strong seismic motion is discussed based on the results of the rapid load pile testing and those of the field monitoring in the beam line. Figure 12 shows the equivalent static load-settlement curve focusing on the load level of the piles in design. Using the static load-settlement curve, the settlement of the

| Cycle | Falling height (m) |
|-------|-------------------|
| 1     | 0.15              |
| 2     | 0.30              |
| 3     | 0.45              |
| 4     | 0.60              |
| 5     | 0.75              |
| 6     | 0.90              |
| 7     | 1.05              |
| 8     | 1.20              |
| 9     | 1.35              |
| 10    | 1.50              |
| 11    | 1.50              |
| 12    | 1.65              |
| 13    | 1.80              |
| 14    | 1.95              |
| 15    | 2.10              |
| 16    | 2.25              |

Fig. 10. Load signals at pile head.

Fig. 11. Rapid load-settlement curves together with equivalent static load-settlement curve.

Fig. 12. Hysteretic curve of load-unload vs. settlement.

Fig. 13. Residual settlement vs. equivalent static load.
test pile subjected to pile-head load of 1.71 MN, which was the measured value on Pile P1 just before the earthquake, was calculated to be 3.3 mm. This value may correspond to the pre-earthquake settlement of a single pile. Figure 13 shows the residual settlement vs. the equivalent static load relationship. It was found that the equivalent static load under the yield load of 6.4 MN caused some residual settlements and the residual settlement at the 4th load cycle was 1.0 mm. Here, the yield load was obtained from the equivalent static load vs. the settlement relationship in double logarithmic scale.

To consider the behavior of the test pile under the seismic loading condition, the equivalent static unload-settlement line was derived from the 4th load cycle of the pile testing since the equivalent static load of 3.06 MN was nearly equal to the maximum axial load in the seismic design. The hysteretic curve of the equivalent static load-unload vs. settlement was shown in Figure 12. Based on the hysteretic curve, the increment in settlement, $\delta$, due to the loading from 1.71 to 3.06 and the unloading to 1.71 MN was calculated to be 0.6 mm. The increment in settlement of the piled raft may be estimated by multiplying a settlement ratio to the calculated increment in settlement of the single pile (0.6 mm), where the settlement ratio gives the ratio of the flexibility of a pile in the group to that of an isolated pile (Poulos and Davis, 1980).

Since the measured settlement of the piled raft just before the earthquake was 20.7 mm and the calculated pre-earthquake settlement of the single pile was 3.3 mm, the settlement ratio was calculated to be 6.3. Therefore, the increment in settlement of the piled raft was estimated to be 3.8 mm (0.6 mm x 6.3). The estimated increment in settlement of the piled raft roughly agreed with the measured value of 4.1 mm.

5 CONCLUSIONS

A mechanism of the increase in settlement of a piled raft supporting a low-rise building, subjected to the strong seismic motion during the 2011 off the Pacific coast of Tohoku Earthquake, is discussed. Using a hysteretic curve of equivalent static load-unload vs. settlement, derived from a rapid load pile testing, and a settlement ratio obtained from the results of the pile testing and the field monitoring, the increment in settlement of the piled raft was estimated to be 3.8 mm which roughly agreed with the measured value of 4.1 mm.

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