Groundwater level lowering effects for reducing damage to existing residences during earthquakes

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Numerous structures, including residences and buildings, were damaged severely not only in Tohoku but also in Ibaraki, which is adjacent to Fukushima, one Tohoku prefecture affected by the Great East Japan Earthquake that struck on 11 March 2011. One difficulty presented by the great earthquake is the method used to reconstruct damaged residences. Another difficult issue is how to maintain the stability of existing structures on sandy soil deposits with high ground water level (GWL) against the coming great earthquakes. Those structures are endangered by liquefaction-induced damage, particularly vulnerable are aged structures that experienced the great earthquake. This study specifically examines a proposal for reducing the settlement and deformation of existing structures on sandy ground during earthquakes. Model tests were conducted under normal gravity ($1 \times g$) conditions to examine the effects of groundwater level lowering techniques with and without sheet pile walls installed along the sides of structures. Analysis of the test results showed the following: (1) Severe structural settlement occurred when no sheet pile walls on sands with high water level had been installed. However, the longer the sheet pile walls had been installed, the more they reduced settlement during earthquakes. (2) Furthermore, the combined use of sheet pile wall installations and a decrease in groundwater level engendered the greatest reduction in structural settlement. (3) It is greatly advantageous from a practical perspective that it is not necessary to attach sheet pile walls to the side walls of structures when the groundwater level becomes lower. Therefore, it is strongly recommended that groundwater lowering techniques should be combined with sheet pile installation for reducing the damage to existing residences during earthquakes.

Keywords: liquefaction, earthquake, groundwater level lowering, existing residence, sheet pile

1 INTRODUCTION

The Great East Japan Earthquake, 11th March 2011, triggered liquefaction leading to severe damage for residences in Ibaraki Prefecture, Japan as shown in Fig. 1. Since then, the local governments started preparation for the coming large earthquake in the near future. In some cities, town and villages, the countermeasure works have been going on but other areas have been still underway for finding the suitable solution for the coming liquefaction because there are some difficulties in the countermeasures for the existing residential houses in comparison with proposal of the countermeasure for constructing the new houses (Yasuhara et al. 2012 and Yasuhara et al.).

Fig. 1. Distribution of liquefaction-induced damaged residences in Ibaraki prefecture, Japan.

In order to develop the countermeasures for the existing structure against the liquefaction, based on the above-mentioned situation, several series of a 1g model tests were carried out. In particular, the model tests aimed to confirm the effectiveness of the countermeasures for mitigation of settlements under liquefaction by adopting the methods of (i) lowering of groundwater level (GWL) and (ii) installation of a sheet pile wall, independently or jointly. That is to say, after carrying out model tests for confirmation of the individual method, tests with the combined use of two methods were also conducted.

2 OUTLINE OF 1 x g MODEL LABORATORY TESTS

The model tests conducted in a laboratory under 1 x g conditions were done using a small-scale soil tank as shown in Fig. 2. The tank dimensions were 100 cm length, 50 cm height, and 20 cm width, respectively. The soil tank was rigidly connected to the shaking table, as shown in Fig. 2. The model ground was prepared using Toyoura sand, which is widely used for geotechnical liquefaction tests in laboratories in Japan. To produce the loose ground, which is easily liquefied, the model ground was produced to have relative density of $D_r=30\%$. The model foundation structure was prepared to simulate the foundation of “a medium-rise building” having unit weight of 20.28 kN/m^3 . A scale of model of the structure had 10-cm length, 16-cm height, and 19-cm width. Then five displacement transducers,

five pore water pressure gages, and three acceleration meters were installed onto the model ground and measurements were conducted for the displacement of both the ground and the structure, changes of the pore water pressure, and acceleration. The model ground was given by vibrating loads with a sinusoidal wave, which has 5 Hz frequency and 200 Gal of acceleration to liquefy the model ground completely.

2.1 Procedure of 1 x g model tests

Model tests were conducted by following the procedures described below:

(1) Dry Toyoura sand was poured into the soil tank using an air pluviation method up to 390 mm from the bottom of the soil tank. At ground depths of 170, 210, 250, 290, 370, and 390 mm, colored Toyoura sand was deposited to form 2 mm thickness for measurement of the ground movement after shaking. The model structure was placed onto 290 mm ground depth. Thereafter, the model sheet piles were installed at the ground level of the end edge of the sheet piles with and without being adhered to the structure wall.

(2) The groundwater was provided from the bottom through the water tank and was raised to the ground surface of the soil tank, as shown in Fig. 2. The rate of rising groundwater was 0.65 mm/min.

Fig. 2 Schematic drawing of 1 x g model testing apparatus.

(3) When the groundwater level was lowered, the groundwater was once raised to ground level, then it was kept for 15 min as it was. Subsequently the groundwater was drained at 0.65 mm/min of rate.

(4) After raising or lowering the groundwater, the model ground was given by shaking loading. During and after shaking, the displacement of the ground surface and the structure, pore water pressures and ground acceleration were measured using instruments attached at the soil tank, as shown in Fig. 2.

3 SCHEMES, RESULTS AND INTERPRETATIONS OF MODEL TESTS

3.1 Test conditions

The test conditions are presented in Table 1. The details are explained as below:

- (1) *Case 1-1*: with no countermeasures as a milestone
- (2) *Cases 1-2* and *1-3*: for checking the effects of GWL
- (3) *Cases 2-1*, *2-2* and *2-3*: for checking the effects of the sheet pile wall length with coherence to structure
- (4) *Cases 3-1*, *3-2* and *3-3*: for checking the effects of the sheet pile wall length without coherence to structure
- (5) *Cases 4-1 to Case 4-4*: For checking the effects of the combined use of two methods

As presented in Fig. 3, the following three positions of GWL are assumed: (i) 0 mm, Ground Surface; (ii) 100 mm, Bottom of Structure; and (iii) 150 mm, Bottom assumed as the slip failure surface.

The lengths of the sheet pile walls were adopted as four cases, 0, 50, 100 and 150 mm from the bottom of the structure, respectively, as presented in Fig. 4.

3.2 Effects of lowering of groundwater levels

Fig. 5 presents results obtained from the tests of the influence of the location of GWL on structural settlement. The settlements of structure clearly decrease concomitantly with increase in lowering of GWL. Fig. 6 presents the time history of the pore water pressure ratios during shaking in different GWL conditions. The results presented in Fig. 6 indicate that the lower GWL induces a smaller incremental generation of the excess pore water pressures. It might result from the lack of occurrence of liquefaction itself by lowering GWL¹⁾. These results confirmed that the lowering of GWL is more effective for protection against the occurrence of liquefaction.

Table 1 Test conditions of $1 \times g$ model tests performed

Test No.	GWL from ground surface (mm)	Sheet Pile Walls	
		Length (mm)	Cohered to structure
Case 1-1	0	0	-
Case 1-2	100	0	-
Case 1-3	200	0	-
Case 2-1	0	50	No
Case 2-2	0	100	No
Case 2-3	0	150	No
Case 3-1	0	50	Yes
Case 3-2	0	100	Yes
Case 3-3	0	150	Yes
Case 4-1	100	50	No
Case 4-2	100	100	No
Case 4-3	150	50	No
Case 4-4	150	100	No

Fig. 3 Locations of GWL

Fig. 4 Locations of sheet pile wall installed.

Fig. 5 Effects of groundwater level on liquefaction.

3.3 Effects of Sheet Pile Walls

Fig. 7 presents test results obtained when particularly addressing the effects of installation of sheet pile walls on settlements of structures. This figure also presents the effects of adhering sheet pile walls to the side walls of structures. Fig. 7 shows that settlement decreases concomitantly with increasing the

Fig. 6 Time history of excess pore water pressures

Fig. 7 Effects of sheet pile walls against settlement.

length of the sheet pile walls without adhering to the structure. As shown in Fig. 8(a) and Fig. 8(b), ground movements during liquefaction are clearly mitigated by installation of the sheet pile walls. It may be caused by blocking the ground movement by sheet pile walls (Shibata et al. 2006). Regarding coherence of the sheet pile walls to structures, in this case, neither are decreased the settlement or ground movement, although the sheet pile wall lengths increase, as shown in Fig. 7, which might be caused by a change of the slip surface during liquefaction. If the sheet pile walls are not adhered to the structure, then the slip surface is assumed to appear at the bottom of the structure, as shown in Fig. 9(a). Therefore, the ground movements might be blocked by installation of the sheet pile walls. However, if the sheet pile walls are adhered to the side walls of structures, then the slip surface might appear at the end tip of the sheet pile walls (see Fig. 9(b)) because the structures are settled together with the sheet pile walls and because the ground is surrounded with the sheet pile walls as shown in Fig. 8(c). Therefore, the settlements are not decreased with adherence to the structures. However, even if the sheet pile walls are adhered to the structure, the settlement

(a) With no sheet piles

(b) With 150 mm sheet piles without cohering

(c) With 150 mm sheet piles cohered

Fig. 8 Ground movements after shaking.

might be mitigated when the assumed slip surface is located into the non-liquefiable layer, as shown in Fig. 10 (Yasuhara et al. 2009, Nishiwaki et al. 2009). That might be an appropriate issue for further study.

3.4 Effects of Two Methods Combined

The above results demonstrate that it might be more effective against the settlement reduction during liquefaction if two methods of the lowering of GWL and the installation of the sheet pile walls without adherence to the structures were put into combined use. Fig. 11 presents the effects of the lowering of GWL for settlement of the structure and the effects of the lengths of the sheet pile walls. Fig. 12 presents the effects of the length of the sheet pile walls on settlement of the structure and the lowering of GWL. From these figures, the following two tendencies were found:

- (1) When two methods are used together, the settlements during shaking are markedly decreased.

(a) Without coherence of sheet pile wall to structure

(b) With coherence of sheet pile wall to structure

Fig. 9 Schematic of ground movements after liquefaction with settlement of structures.

Furthermore, the combined two methods are more effective for reducing the settlement of the structure

Fig. 10 Schematic of ground movements after liquefaction on a non-liquefiable layer.

during liquefaction, in comparison to effects in the cases of each countermeasure being adopted independently (Motohashi et al. 2010).

(2) When the sheet pile walls are installed into the non-liquefiable layer, settlement remains nearly the same as that in the case of both lowering of GWL and extending the sheet pile walls to the bottom of the assumed slip surface being adopted, as shown in Fig. 11. From this perspective, both methods might show equivalent effects on reduction of the settlements during earthquakes. Therefore, when the GWL cannot be lowered because of the risk of ground settlement, the combined methods can be adopted (Motohashi et al. 2010). They might be effective against the reduction of settlement induced by liquefaction.

4 PRACTICAL APPLICATION OF TEST RESULTS

The amount of ground dewatering corresponding to the allowable value of the settlement vs. width of structures can be determined using the test results obtained in the laboratory. Some results are shown schematically in Fig. 13. This application can be extended to the construction of the design chart if we combine the laboratory test results with those observed in the field.

5 CONCLUSION

Model tests were conducted under normal gravity ($1 \times g$) conditions to examine the effects of groundwater level lowering techniques combined with and without sheet pile walls installed along the sides of structures. Analyses of the test results revealed the following important points.

- (1) Severe structural settlement took place when no sheet pile walls on sand with a high water level had been installed. However, the longer the sheet pile walls had been installed, the greater the reduction of settlement during earthquakes.
- (2) Furthermore, the combined use of sheet pile wall installations and a decrease in groundwater level produced the greatest reduction in structural settlement.
- (3) It is a great advantage from a practical perspective that it is not necessary to attach sheet pile walls to the

Fig. 11 Structural settlement versus length of sheet pile walls.

Fig. 12 Structural settlement of versus groundwater level

Fig. 13 Key sketch for determining the amount of dewatering corresponding to the allowable settlement.

side walls of structures when the groundwater level becomes lower. Therefore, it is strongly recommended that groundwater lowering techniques should be combined with sheet pile installation for reducing damage to existing residences during earthquakes.

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