Study on the mechanism of the liquefaction-induced settlement of structures by case histories and model tests

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ABSTRACT

The mechanism of the liquefaction-induced settlement of structures was studied by two case histories and two large shaking table tests. During the 1964 Niigata earthquake a photographer took a motion picture which showed the settlement of a building started before the eruption of water. Results of a 1G shaking table tests showed that the penetration settlement of a model house occurred first, then ground water spewed out around the model house. The ground surface settled gradually after the occurrence of liquefaction. Based on these case histories and model tests, the authors concluded that a structure did not sink into a hole that was produced by water spewing out, but penetrated into the ground due to a decrease in the shear modulus of the surface layer.

Keywords: liquefaction; settlement; case history; model test

1 INTRODUCTION

Many prediction and remediation methods for liquefaction have been developed since the 1964 Niigata and Alaska earthquakes. The effectiveness of the remediation methods has been proved during past earthquakes. However, a new problem was raised during the 1995 Hyogoken-nambu (Kobe) Earthquake because recorded accelerations were far greater than the design acceleration. Then, studies on the adoption of performance-based design started in Japan. In the performance-based design two items must be developed: methods to estimate the deformation of structures, and the allowable values of deformation of the structures. However, the mechanism by which a structure settles in liquefied ground has not become clear. When the ground liquefies, eruption of muddy water occurs, the building settles, the ground subsides, but the timing of these occurrences is unknown. Then the mechanism of the liquefaction-induced settlement of structures was discussed by two case histories and two large shaking table tests.

2 TIMING OF THE ERUPTION OF MUDDY WATER AND THE SETTLEMETN OF STRUCTURES OBSERVED DURING PAST TWO EARTHQUAKES

During the 1964 Niigata earthquake a professional photographer named Mr. Yuminamochi took a very important motion picture showing the settlement of a terminal building at Niigata Airport and the eruption of water near the building (JGS, 2004). According to his testimony, he was outside the airport building at the onset of the quake. After one or two minutes, he heard someone crying "the building is sinking!". The shaking of the ground had already stopped. This was about 80 seconds after the strong shaking. He remembered that he had an 8 mm motion picture camera and started taking a motion picture. Shortly after, a large volume of muddy water spewed out from the edge of the building and continued to spew for long time. This sequence evidence implies that the settlement started before the eruption of water, and the settlement of the building was caused statically by the force of gravity on the building.

The authors sent out questionnaires to about 30 inhabitants in Urayasu City to ask the timing of eruption of muddy water during the 2011 Great East Japan (Tohoku) Earthquake (Yasuda et al., 2012). Answers are summarized in Fig. 1. About 1/3 of the persons observed the boiling of muddy water immediately after the main shock. Other persons found the muddy water at different timing. Liquefaction occurred during aftershock at some sites. Question on the timing of the settlement of houses must be difficult to answer for inhabitants.

3 TIMING OF THE ERUPTION OF WATER AND THE SETTLEMETN OF MODEL HOUSES MEASURED BY SHAKING TABLE TESTS

3.1 Shaking table test on a raft foundations in liquefied ground

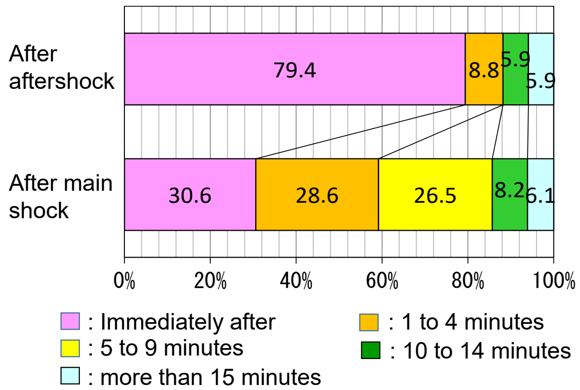


Fig. 1. Questionnaires to inhabitants to ask the timing of eruption of muddy water during the 2011 Great East Japan (Tohoku) Earthquake.

In 1995, Hyogoken-nambu (Kobe) earthquake brought violent damages to pile foundations for high pressure gas tanks. Then shaking table tests were conducted to demonstrate the behavior of pile foundations and a raft foundation (Yasuda et al, 2000). A large-scale shaking table and a laminar shear box developed by the National Research Institute for Earth Science and Disaster Resilience in Japan was used. The box, which has a height of 6 m, length of 12 m, and width of 3.5 m, consists of 29 laminar frames of 20 cm height is designed to deform more than 1m in one horizontal direction, as shown in Fig. 2. Three types of real-size pile by different connecting methods between footings and pile tops, were fixed on the bottom of the box as shown in Fig.3. A concrete block with 0.9 m in width, 1.2 m in length and 1.86 ton in weight also placed on the ground surface to demonstrate the behavior of settlement of raft foundation. Relative density and water level of the model ground were 61% and GL-0.2m, respectively.

Shaking motion was applied in one direction parallel to the horizontal axis in the figure at a frequency of 1 Hz. Three steps of input acceleration, 150, 300 and 400 gals were applied for 30 seconds in each step with appropriate interval times to dissipate excess pore pressure. Acceleration, pore pressure and shear displacement in the ground were measured by accelerographs, piezometers and a special shear displacement transducers, respectively. Strain of the piles and displacement of the footings were measured by strain gauges and displacement transducers, respectively. The raft foundation settled 6 cm during shaking. As the ground surface subsided 1.6 cm, the relative settlement of the raft foundation during shaking was 4.7 cm. In addition, surprisingly, water and sand started to spew out on the ground surface about one minute after the stopping of shaking, then the raft foundation started to settle again as shown in Fig.4. The raft foundation settled gradually and sank under the ground surface. The final settlement of the foundation was 51cm. As the ground surface was subsided 9.5cm, the final relative settlement of the foundation was 41.5cm.

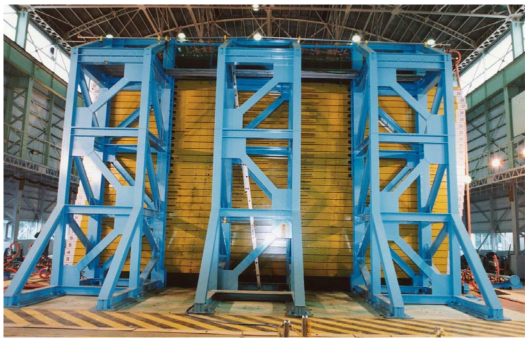


Fig. 2. A large-scale shaking table and a laminar box.

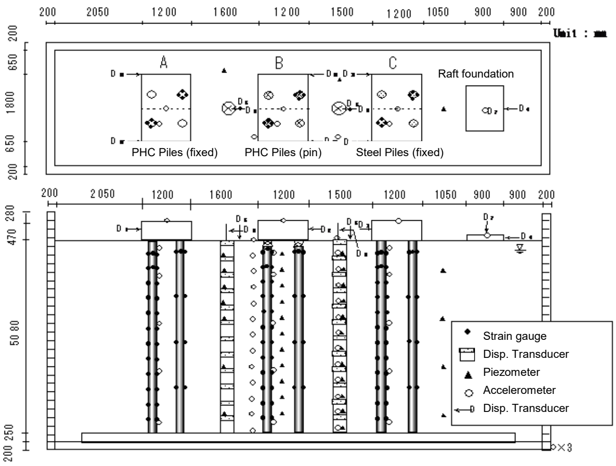


Fig. 3. Model pile foundations and a model raft foundation.

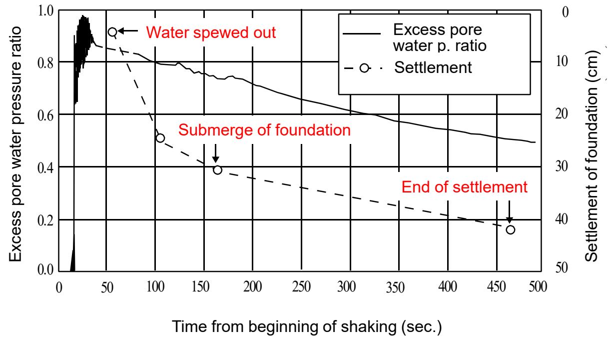


Fig. 4. Time histories of the settlement of the raft foundation.

3.2 Shaking table test on a house in liquefied ground

According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan, about 27,000 wooden houses were damaged due to liquefaction by the 2011 Great East Japan Earthquake (Tohoku) Earthquake. Then model tests by using a large shaking table and a soil container owned by the Building Research Institute in Japan were carried out to demonstrate the effectiveness of enclosing the foundation soil of a 1/4 scale house with sheet piles to counter settlement and tilting (Kaneko and Yasuda, 2014). Six tests were conducted, one without sheet piles (Case 2) and the others with sheet piles of different depths and widths. Among them test results for Case 2 are discussed in this paper. Model grounds consisted of two sand layers, an upper, 2.5 m thick, loose layer with a relative density of 40% and a lower, dense layer with a relative density of 80% as shown in Fig.5. The ground water table was controlled at a depth of 0.25 m. The ground contact pressure of the model houses was 19.5 kN/m^2. A sine wave of shaking with a frequency of 2 Hz was applied for 60 seconds to induce liquefaction. Many accelerometers and pore water pressure transducers were installed in the ground. Settlement transducers were installed on the model house and on the ground surface. Penetration settlement was estimated by subtracting the settlement of the ground surface from the total settlement of the model house.

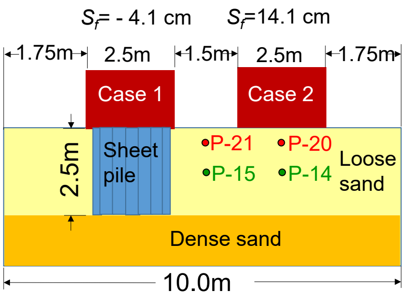


Fig. 5. Diagram of large 1G shaking table test.

Figures 6 (1) and 6 (2) show time histories of the excess pore water pressure ratio measured by four transducers shown in Fig. 5. At P-21 and P-15, which were installed in the ground between two model houses at depths of 0.3 m and 1.5 m, respectively, pore pressure increased rapidly after the beginning of shaking, reaching maximum values at about 5 seconds. As the maximum excess pore water pressure ratio reached about 1.0, it is estimated that the upper loose sand layer liquefied after about 5 seconds of shaking. The excess pore water at P-14, which was installed at 1.5 m below the model house, increased to a maximum value at about 5 seconds, then slightly decreased. On the contrary, the pore water pressure at P-20, which was installed at 0.30 m below the model house, did not start to increase until 5 seconds, then increased gradually, reached a maximum value at about 32 seconds. The increase of the pore water pressure after 5 seconds must have been induced because of the propagation of the excess pore water pressure generated in a lower liquefied layer, such as near P-14. Due to this propagation, the pore water pressure at P-14 must have decreased slightly from 5 seconds to 30 seconds.

Figure 6 (3) shows time histories of the penetration settlement in Case 2 and Case 1. In Case 2, the house settled about 1 cm just after the beginning of shaking due to insufficient contact between the footing of the model house and the ground surface. After that, penetration settlement increased a little, accelerated from about 15 seconds to 38 seconds, then decelerated. The excess pore water pressure ratio at P-20 reached about 0.4 at about 15 seconds, as shown in Fig. 6 (2). Therefore, it can be said that the penetration settlement (sinking into ground) accelerated due to the softening of the ground.

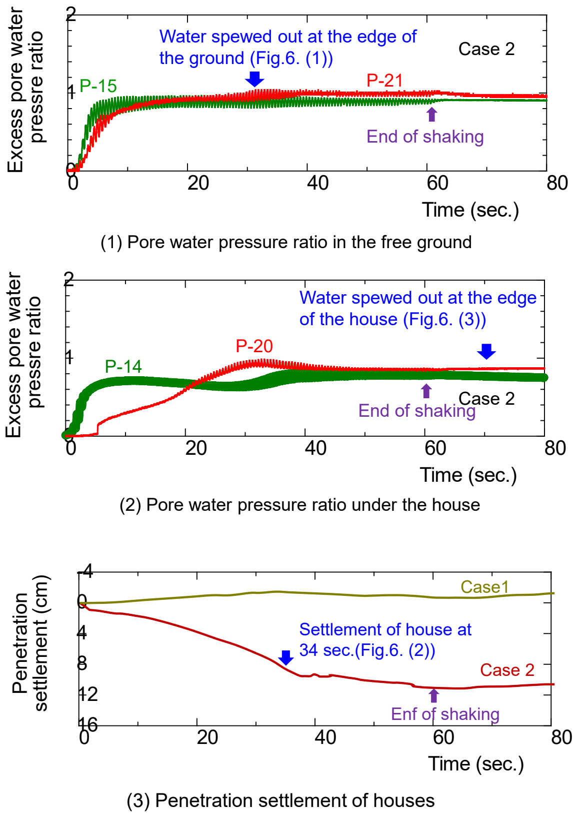
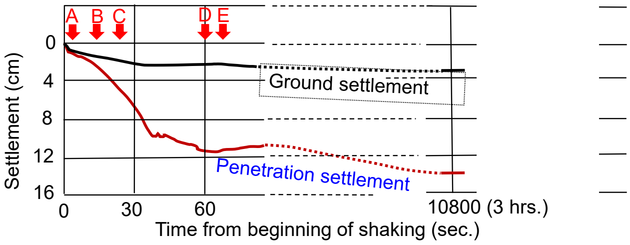


Fig. 6. Time histories of penetration settlement and pore water pressure ratio for Case 1.

Figures 7 (1) , 7 (2) and 7 (3) show the behavior of the model house and surrounding ground at 26, 34 and about 70 seconds, respectively. As shown in Fig. 7 (1), water started spewing out of the ground at 26 seconds at the edge of the model ground. However, water did not spew out of the ground until the end of shaking around the model house, but spewed out several seconds after the end of shaking, as shown in Figure 7 (3). On the contrary, the penetration settlement accelerated at about 15 seconds, as mentioned above, and, at 34 seconds, reached about 8 cm, which is about 80% of the settlement at the end of shaking. Figure 8 summarizes the timing of the occurrence of liquefaction (A), penetration settlement accelerated (B), water spewing out at the edge of the ground (C), the end of shaking (D), and water spewing out at the edge of the house (E), with the time histories of the ground and penetration settlements. As shown in this sequence, penetration settlement occurred first, then ground water spewed out around the model house. The ground surface settled gradually after the occurrence of liquefaction.

(1) Spewed water at the edge of the ground at 26 sec.
(2) Penetration settlement at 34 sec.
(3) Spewed water at the edge of house around 70 sec.

Fig. 7. Photographs of penetration settlement, heaving, and spewed water.



A: Loose sand liquefied
B: Penetration settlement accelerated
C: Water spewed out at the edge of the ground
D: End of shaking
E: Water spewed out at the edge of the house

Fig. 8. Time histories of penetration settlement and ground settlement.

4 DISCUSSIN ON THE PROCESS ON THE MECHANISM OF THE SETTLEMENT OF A STRUCTURE

Based on the case histories during past earthquakes and the model tests, the authors concluded that a structure such as a building or a house did not sink into a hole that was produced by water spewing out, but penetrated into the ground due to a decrease in the shear modulus of the surface layer following the outside lateral flow of the ground under the house and the heaving of ground surrounding the house, as schematically shown in Figure 9. The ground surface settled slowly because the liquefied layer under and around the house densified gradually due the spewing out of the pore water.

5 CONCLUSION

The mechanism of the liquefaction-induced settlement of structures was studied by two case histories during the 1964 Niigata and the 2011 Tohoku earthquakes, and two large shaking table tests. Results showed penetration settlement of a structure occurred first, then ground water spewed out around the structure. Therefore it was concluded that the structure did not sink into a hole that was produced by water spewing out, but penetrated into the ground due to a decrease in the shear modulus of the surface layer, then the ground surface settled gradually.

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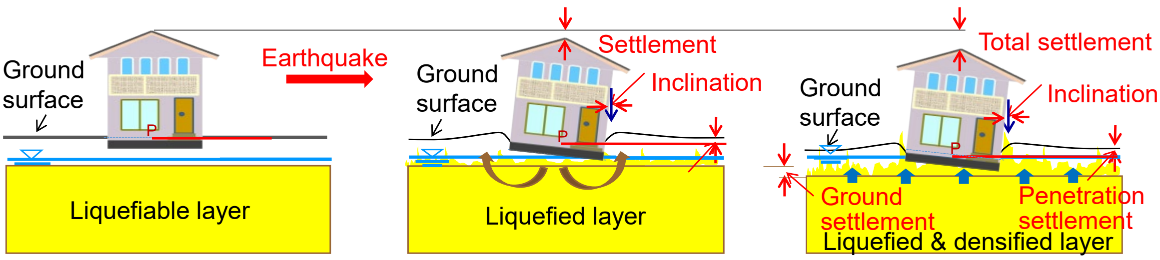

Fig. 9. Mechanism of liquefaction-induced settlement of a house and ground.