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URBAN LIQUEFACTION COUNTERMEASURE PROJECT APPLIED TO CHIBA AND OTHER CITIES AFTER THE 2011 TOHOKU EARTHQUAKE

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Abstract

New measures have been taken to lower the groundwater level in six cities that were affected by liquefaction due to the 2011 Tohoku Earthquake (Great East Japan Earthquake). The authors have developed these measures and verified their effectiveness in several cities, and this paper reports the results. In particular, since a detailed study was conducted in Chiba City, this paper focuses on Chiba City.

According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), about 27,000 wooden houses were damaged due to liquefaction by the Tohoku Eartquake. The MLIT established a new project, the "Urban liquefaction countermeasure project". In this project, a wide residential area, including roads, buried pipes and more than 10 houses, is treated by an appropriate countermeasure and its costs are shared by the government and inhabitants. The project aimed to select effective countermeasures and determine how to share their cost with inhabitants. The method of lowering the ground water table has been selected as the most promising for several cities.

In this project, it was necessary to determine: i) how much to lower the water table, ii) how to lower the water table, and iii) how much subsidence occurs accompanying the lowering of the water table. By comparing the ground water tables in areas where houses were damaged and in areas where housed were not damaged during the Tohoku Earthequake, the government concluded that a water table of about 3m below the ground surface ensured safety against damage due to liquefaction. In-situ tests were carried out in eight cities. In Chiba City, two rows of drainage pipes 20 cm in diameter were buried at a depth of GL-3.4 m with a distance of 39 m. The water table was lowered from about GL-1 m to about GL-3 m by pumping up the water collected in two manholes from drain pipes. Test results showed that the ground water table could be lowered to a depth of about GL-3 m even in the center between two drainage pipes. The ground settlement due to the consolidation of the alluvial clay layer was very small, about 1cm. The pore water pressures before and after dewatering did not decrease at deep layers but decreased at shallow depths only.

Based on the in-situ tests, drainage pipes were constructed in Tokai Village, Kashima City, Kamisu City, Itako City, Chiba City and Kuki City. Measurement of the depth of the water table, the settlement of the ground surface and the pore water pressure were conducted during and after the construction of drainage pipes. According to the measured values at Isobe 4-chome in Chiba City, total settlement was small, less than 1 cm, almost same as the settlement in the in-situ test. The ground water level decreased in the whole area to a sufficient level. Similar results were also obtained in other cities.

Keywords: liquefaction; countermeasure; residential area; groundwater table

1. Introduction

The 2011 Tohoku Earthquake caused severe damage to many residential areas in Japan due to liquefaction. Wooden houses settled and tilted, roads were thrust out of alignment and underground pipes were disconnected. In Japan, many remediation methods against liquefaction have been developed since the 1964 Niigata Earthquake, which caused severe damage to structures due to liquefaction. The remediation methods have been applied to many kinds of structures, such as oil tanks, quay walls, bridges and buildings. However, in the design of wooden houses, liquefaction had not been considerd. Settled houses were restored by lifting them, and roads and underground structures were repaired after an earthquake. However, many inhabitants face the serious problem of preventing re-liquefaction during future earthquakes. Thus, the Ministry of Land, Infrastructure, Transport and Tourism established a new project, the "Urban liquefaction countermeasure project" and organized a technical committee to propose appropriate countermeasures. Based on this committee's proposal, technical committees were organized in several local governments to investigate the possibility of applying the proposed countermeasures. One of the proposed measures was lowering the ground water level in residential areas. The adaptability of this method was demonstrated by in-situ tests, and then applied in six cities and one village. The authors have joined the technical committees and consulted on the restoration works. Now, almost all restoration work has been done. In this paper, the process of the project is described, mainly in reference to Chiba City.

2. Damage to wooden houses, roads and lifelines in residentioal areas due to liquefaction

During the 2011 Tohoku (Great East Japan) Earthquake, liquefaction occurred in the Tohoku region of northeastern Japan and in the Kanto region surrounding Tokyo because the earthquake was huge. According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), about 27,000 wooden houses were damaged due to liquefaction. The geomorphologic conditions of sites of liquefaction were as follows: i) artificially reclaimed lands along Tokyo Bay and the Pacific Ocean, ii) filled grounds on former ponds and marshes in lowlands, iii) sites excavated to get iron sand or gravel and then refilled, and iv) filled sloping grounds on hills or terraces. On flat land with a liquefied layer of uniform thickness, uniform subsidence occurred due to the change in volume of the liquefied layer and houses penetrated into the ground at some inclination due to the loss of bearing capacity or due to a decrease in the shear modulus of the liquefied layer, as shown in Figs. 1 and 2.

Fig. 1 - Settled and tilted houses in Urayasu City

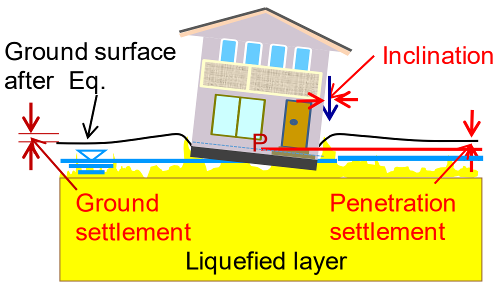


Fig. 2 - Schematic diagram of a settled and tilted house

Two months after the earthquake, the Japanese Cabinet announced a new standard for the evaluation of damage to houses based on two factors, settlement and inclination, as shown in Table 1 (Yasuda and Hashimoto, 2016). A new class of "large-scale half collapsed house" was introduced, and houses tilted at angles of more than 50/1,000, of 50/1,000 to 16.7/1,000, and of 16.7/1,000 to 10/1,000 were judged to be totally collapsed, large-scale half collapsed and half collapsed houses, respectively, under the new standard. Thus, liquefaction-induced damage to houses was evaluated mainly by their inclination. The penetration settlement of houses damages water and sewage pipes, but these pipes can be strengthened easily against settlement by using flexible joints and other measures. And, the uniform ground settlement of an area due to the densification of the liquefied layer did not prevent inhabitants from performing their daily activities. On the contrary, in the steeply tilted houses, inhabitants felt giddy and nauseas and could not live in their houses after the earthquake, though the walls, pillars and windows of the houses had no damage.

Table 1 - New evaluation standard announced by the Japanese Cabinet

Grade of damage		Totally collapsed	Large-scale half collapsed	Half collapsed	Partially damaged
Evaluation criterion	Inclination	> 50/1000 	16.7/1000 to 50/1000 	10/1000 to 16.7/1000 	<10/1000
	Settlement	Floor 1m or more below the ground surface	Floor rests on ground surface	25cm above the ground surface	

At many flat roads in residential areas, liquefaction caused several phenomena that interrupted traffic: i) much muddy water boiled onto roads (Fig. 3), ii) road asphalt heaved, was thrusted or was deformed into waves at many sites, and iii) many small road cave-ins occurred several months after the earthquake. The duration of shaking during the 2011 Great East Japan Earthquake was extremely long, and the main shock was soon followed by big aftershocks because the earthquake was a "megathrust earthquake" with extremely large magnitude of *M*w=9.0. Shaking continued for a long time after the occurrence of liquefaction. Due to the shaking of the liquefied ground, large horizontal displacement, which is a kind of sloshing of liquefied ground, was induced and caused roads to thrust (Yasuda and Ishikawa, 2014).

Fig. 3 - Muddy water boiled onto roads in Urayasu City (Photo by Mr. Ogawa)

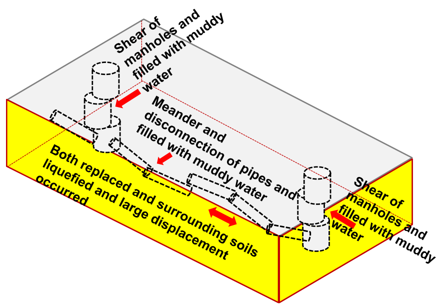


Fig. 4 - Diagram of damage to sewage pipes and manholes due to liquefaction

Water, sewage and gas pipes were also severely damaged in residential areas due to liquefaction. The large horizontal displacement of liquefied ground, mentioned above, exerted large cyclic compressional and tensile stress on sewage pipes in the horizontal direction, resulting in the disconnection of pipe joints and the shear failure of manholes, as schematically shown in Fig. 4, allowing the influx of muddy water into the pipes and manholes (Yasuda and Ishikawa, 2014). Water pipe and gas pipe joints were also disconnected at many sites.

3. Studies on the mechanizm of the penetration settlement and the inclination of wooden houses conducted after the earthquake

One of the authors and his colleagues conducted model tests using a large shaking table and a soil container owned by the Building Research Institute in Japan to demonstrate the mechanism of the penetration settlement of houses due to liquefaction. 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. A sine wave of shaking with a frequency of 2 Hz was applied for 60 seconds to induce liquefaction. Two 1/4 scale houses with (Case 1) and without (Case 2) sheet piles were placed on the ground. Figs. 6 (a) , 6 (b) and 6 (c) show the behavior of the model house and surrounding ground at 26, 34 and about 70 seconds, respectively (Yasuda and Ishikawa, 2019). As shown in Fig. 6 (a), 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 Fig. 6 (c). On the contrary, the penetration settlement accelerated at about 15 seconds, and, at 34 seconds, reached about 8 cm, which is about 80% of the settlement at the end of shaking. Figure 7 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. Based on 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 Fig. 8. The ground surface settled slowly because the liquefied layer under and around the house densified gradually due the spewing out of the pore water.

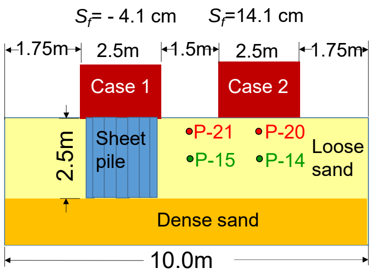
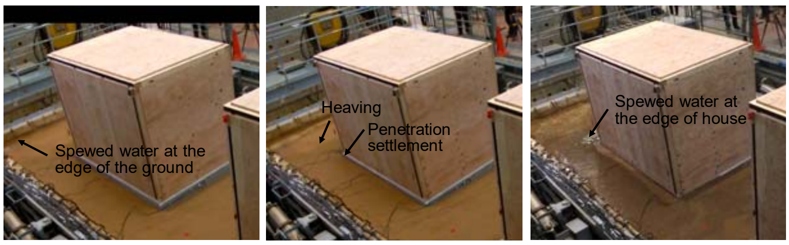


Fig. 5 - Diagram of large 1G shaking table test



(a) Spewed water at the edge of the ground at 26 sec. (b) Penetration settlement at 34 sec. (c) Spewed water at the edge of house around 70 sec.

Fig. 6 - Photographs of penetration settlement, heaving, and spewed water

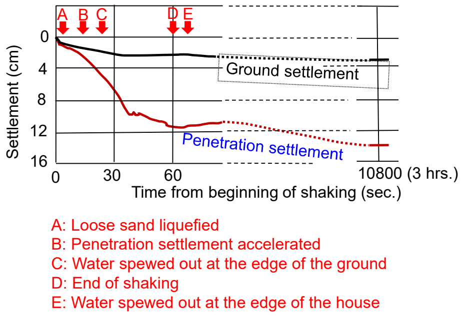
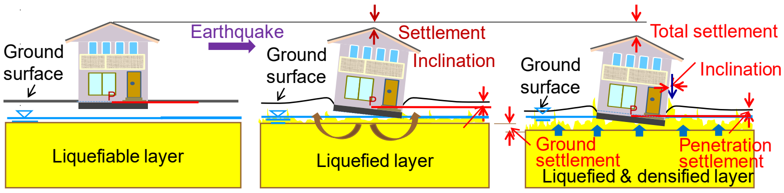


Fig. 7 - Time histories of penetration settlement and ground settlement



(a) Before earthquake (b) During and/or a few minutes after earthquake (c) Several minutes or hours after earthquake

Fig. 8 - Mechanism of liquefaction-induced settlement of a house and ground

The tilting of houses is derived from non-uniform settlement. According to the authors' previous study on the non-uniform settlement of houses, several factors affect non-uniform settlement. Among them, the effect of adjacent houses was dominant, as schematically shown in Figs. 9 and 10. If two houses are close to each other, they tilt inward toward each other, and if four houses are close, they tilt toward their common center. Figs. 11 (a) and 11 (b) show the actual relationship between the penetrating settlement and the inclination of houses in two cities in which the houses are clustered close together and in two other cities in which the houses are scattered, respectively (Yasuda, 2014). Though these data are scattered, inclination increases with penetrating settlement in each figure. And the relationships are different in two sets of cities.

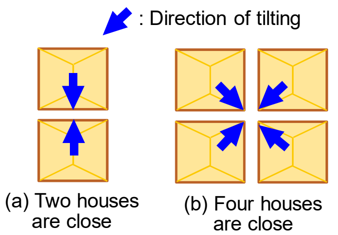


Fig. 9 - Effect of adjacent houses on the inclination of houses

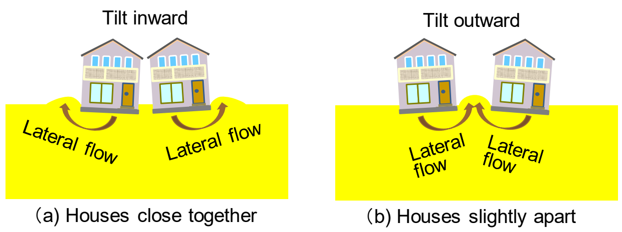
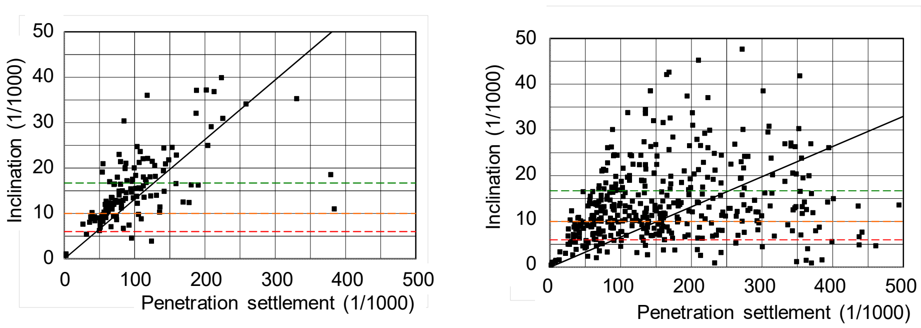


Fig. 10 - Hypothesized mechanism of house tilting due to lateral flow of liquefied soil



(a) In Chiba and Narashino cities, where houses are clustered close together

(b) In Kamisu and Itako cities, where houses are scattered

Fig. 11 - Relationship between penetration settlement and inclination of houses caused by the 2011 Tohoku Earthquake

One of the authors and his colleagues measured the exact depth of the water table at the sites of about 28 damaged houses in the Irifune and Mihama districts of Urayasu City. The measured depths are classified by the level of damage to wooden houses and plotted in Fig.12. As shown in this figure, a water table of about 1.7 to 2.0 m below the ground surface was the critical depth to cause damage to houses. So, the authors assume that the upper non-uniform layer affects the damage to wooden houses as follows (Yasuda and Hashimoto, 2016). When a liquefied layer is of uniform thickness and the upper non-liquefied layer is thin, houses penetrate into the ground, often at an angle, due to the lateral flow of the liquefied layer. In addition, uniform subsidence occurs due to the densification of the liquefied layer. However, if the non-liquefied layer is thick, penetration settlement and tilting is limited, though uniform subsidence due to the densification of the liquefied layer occurs. For the non-liquefied layer, it must be noted that the water table is not stable but increases during shaking for two reasons: i) the inflow of water from the lower liquefied layer due to liquefaction-induced densification, and ii) the spewing out of water due to excess pore water pressure induced in the liquefied layer. The inflow of water from the lower liquefied layer increases the water level by 1 m or less if the thickness and the volumetric strain of liquefied layer is several meters and about 5%, respectively. The water spewed out from the liquefied layer occasionally reaches a few meters above the ground surface, but it flows through narrow spaces, such as cracks in the ground, and lasts for a short time. Therefore, the ground water level usually increases by only a meter or so. Considering this increase in the water table due to liquefaction, a water table of about 2 to 3 m below the ground surface must be the critical depth to prevent damage to a house, as schematically shown in Fig. 13.

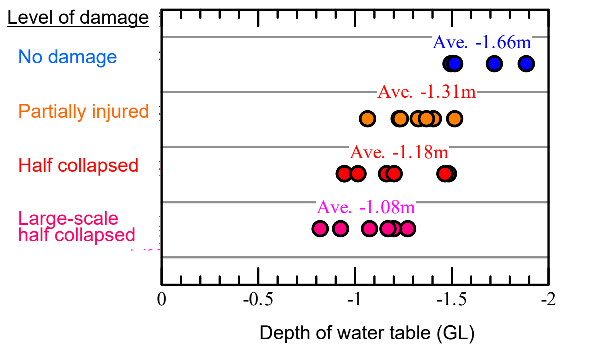


Fig. 12 - Measured depth of water table at sites of damaged and undamaged houses in Urayasu

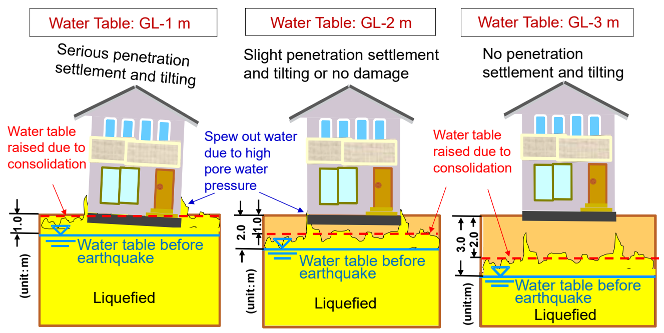


Fig. 13 - Illustration of the impact of the water table on the settlement and tilting of a house

4. Establishment of a new project and conduct of in-situ tests

In residential areas where liquefaction occurred, houses, roads, water pipes, sewage pipes and gas pipes were damaged, interrupting daily life. Many houses have been restored by lifting them, repairing their footings, and replacing them on their footings, and lifelines have been repaired in the three years since the earthquake. However, many inhabitants face the serious problem of how to prevent re-liquefaction during future earthquakes. The MLIT established a new project eight months after the earthquake, the "Urban liquefaction countermeasure project". In this project, a wide existing residential area of more than 3,000 m^2, including roads, buried pipes and more than 10 houses, is treated by an appropriate countermeasure and its costs are shared by government and inhabitants. The project aims to select effective countermeasures and determine how to share their cost with inhabitants. Available countermeasures have been compared in damaged cities, and two methods, lowering the ground water table, as shown in Fig. 14, and surrounding the foundation ground with lattice-type underground walls, have been selected as the most promising. For the method of lowering the water table, it was necessary to decide i) how much to lower the water table, ii) how to lower the water table, iii) how much subsidence occurs accompanying the lowering of the water table, and iv) the cost of each method of lowering the water table. The project decided that a water table of about 3m below the ground surface was appropriate to prevent liquefaction damage to wooden structures in most cities based on a comparison of the water tables where structures had been damaged and the water tables where structures had not been damaged in each city and based on the criterion proposed by MLIT shown in Fig. 15.

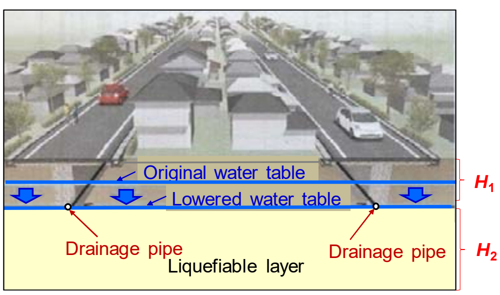
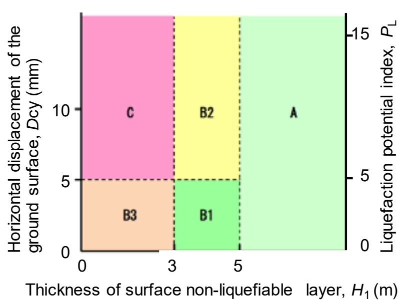


Fig. 14 - Lowering of ground water table



Evaluation results	Potential for liquefaction damage
C	The potential for severe damage is high.
B3	Potential for severe damage is relatively low.
B2	
B1	
A	Potential for severe damage is low.

Fig. 15 - A new method to estimate the liquefaction-induced damage to wooden houses (MLIT, 2014)

In-situ tests were carried out in eight cities to investigate appropriate methods of lowering the water table, how much subsidence occurs with each method, and the cost of each method. Drain pipes were used to lower the water table in Itako, Kamisu, Kuki, Chiba and Kashima cities and in Tokai Village. Shallow wells to a depth of 3m were used in Abiko City and deep wells to a depth of 15m were used in Urayasu City (Yasuda and Hashimoto, 2016). Figs. 16 and 17 show the plane and the soil cross section at the in-situ test site in Chiba City. The in-situ test was conducted at Isobe-4 chome. The test yard was 43.2m in length and 22.0m in width, and was enclosed by sheet pile walls. Two rows of drain pipes 20 cm in diameter were buried at a depth of GL-3.4 m with a distance of 39 m. The water table was lowered from about GL-1 m to about GL-3 m by pumping up the water collected in two manholes from drainage pipes. Test results showed that the ground water table could be lowered to a depth of about GL-3m even in the center between two drainage pipes, as shown in Fig. 18. The ground settlement due to the consolidation of the alluvial clay layer was very small, about 1cm. Pore water pressures measured before and after dewatering showed that pore water pressure did not decrease at deep layers but decreased at shallow depths only as shown in Fig. 19. Moreover, the over consolidation ratios, OCRs, of the soft clay layer were greater than 1.0. The subsidence measured in other cities was also fairly small. According to the time history of accumulated pumped-up water and rain water from the beginning of the test in Chiba City, though much water had to be pumped up to lower the water table at the beginning of the test, a small amount of pumped-up water per day became constant after three to four months. It was estimated that the amount of pumped-up water would be about 1/2 to 1/3 of the amount of rain water.

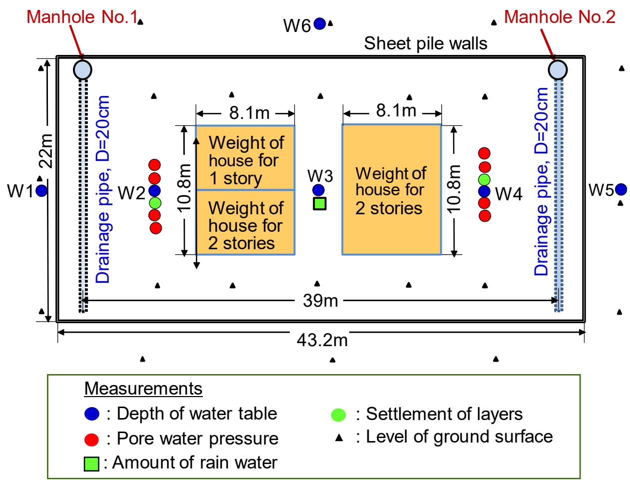


Fig. 16 - Plan of the in-situ test site in Chiba City (Chiba City, 2014)

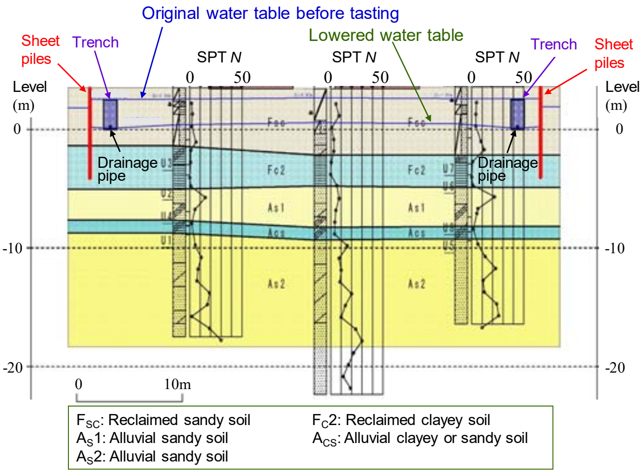


Fig. 17 - Soil cross section at the in-situ test site in Chiba City (Chiba City, 2014)

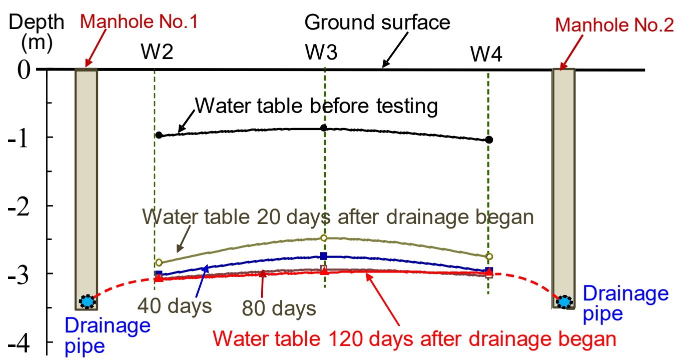


Fig. 18 - Change of the water table during test in Chiba City (Chiba City, 2014)

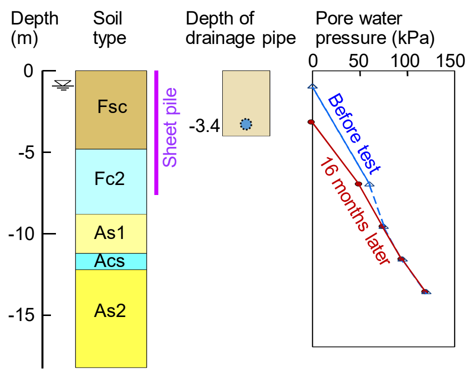


Fig. 19 - Change of pore water pressure during lowering of the water table in Chiba City

5. Construction of drainage pipes and confirmation of the effectiveness of the measure

Among the cities in which the adaptability of lowering the ground water table was investigated, Tokai Village, Kashima City, Kamisu City, Itako City, Chiba City and Kuki City decided to construct drainage pipes. The methods for constructing the drainage pipes, lowering the water level and confirming the effect of these measures in Chiba City and Kashima City are described below.

In Chiba City, a residential area of about 3 km x 10 km was constructed by reclaiming the coast of Tokyo Bay in around 1966 to 1975. Liquefaction occurred over a wide area in this reclaimed land, causing serious damage to many wooden houses, roads and lifelines. Then a technical committee was organized in 2012 to select an appropriate countermeasure to liquefaction as part of the urban liquefaction countermeasure project. Three districts were nominated first: the Isobe, Masago and Makuhari-nishi districts. Then, the applicability of two methods, lowering the ground water table and surrounding the foundation ground with lattice-type underground walls, was investigates by conducting borings and analyses. The possibility of sharing the cost of these measures by the government and local inhabitants was also discussed. Then, it was decided that two districts, Isobe 4-chome and Isobe 3-chome, would lower the ground water table.

Figure 20 shows the layout of drainage pipes in Isobe 4-chome. 260 wooden houses exist in an area of about 7.1 ha. Site "P" is the in-situ test site mentioned before. As shown in Fig. 17, loose, reclaimed, sandy soil is deposited from the ground surface to the depth of 4 m to 6 m. Reclaimed clayey soil is underlaid. The level of the ground surface is about T.P. (Tokyo Peil) + 3m. The depth of the drainage pipes was designed with a slope of 2 mm/1000 mm from northwest to southeast because there is a small river in the southeast

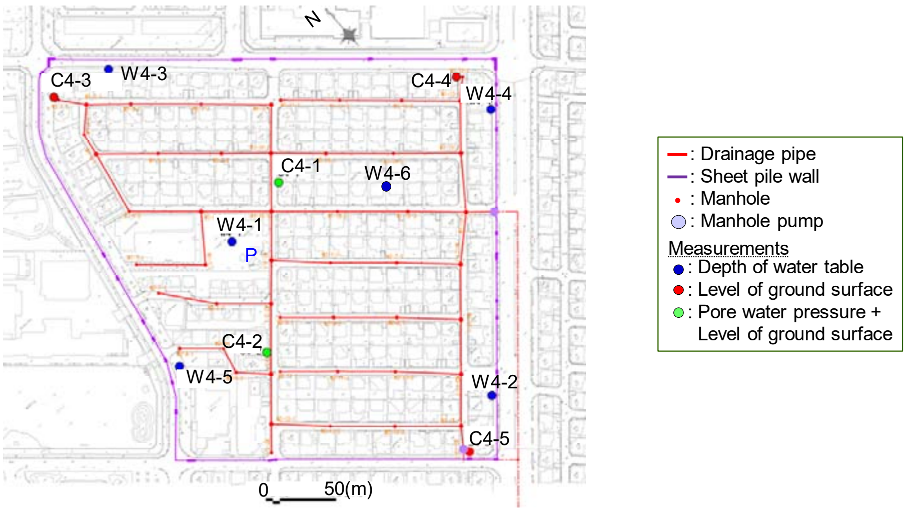


Fig. 20 – Layout of drainage pipes in Isobe 4-chome in Chiba City (Chiba City, 2019)

Fig. 21 – Houses clustered close together in Isobe 4-chome

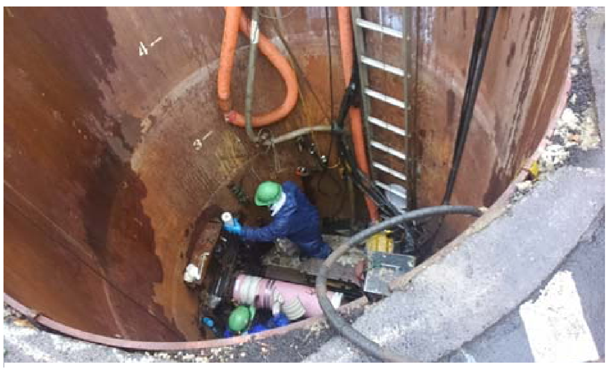


Fig. 22 – Installation of a drainage pipe from a shaft

direction. Drain water flows through the drainage pipes into two manholes located at the southeast boundary of the area, then the water is pumped up and into a pipe connecting to the river. The standard method to construct a drainage pipe at a shallow depth is to excavate a trench, place a drainage pipe and backfill the trench with sand. However, noise, vibration and traffic obstruction generated by construction were concerns because houses are clustered close together in this area, as shown in Fig. 21. Thus, the drainage pipes were placed by a special shield method. Vertical shafts of about 2.5 m in diameter were constructed at intervals of about 50 m, and then specially made drainage pipes of 30 cm in diameter were installed from the shafts, as shown in Fig. 22. Later, manholes were constructed in vertical shafts. The distance between drainage pipes was planned as 40 m, and the planned depth of the pipes was GL-3 m, as in the in-situ tests. Sheet pile walls were installed to a depth of about 6 m around the district to prevent water flow from outside the area. Many sensors were installed to measure the depth of the water table, the settlement of the ground surface, the pore water pressure during and after the construction of drainage pipes.

After the construction of drainage pipes and sheet piles, water drainage started from September 3, 2018. To prevent local subsidence induced by a rapid decrease in the ground water level, plugs were installed in the drainage pipes to control the decrease. Figure 23 shows time histories of the ground water level and the settlement of the ground surface for one year from the start of drainage. Daily rainfall is also plotted in the figure. The ground water table decreased to about GL-2.2 m to -2.9 m in one year due to the drainage from an original ground water level of about GL-1.2 m to -1.6 m. As shown in this figure, short increases in

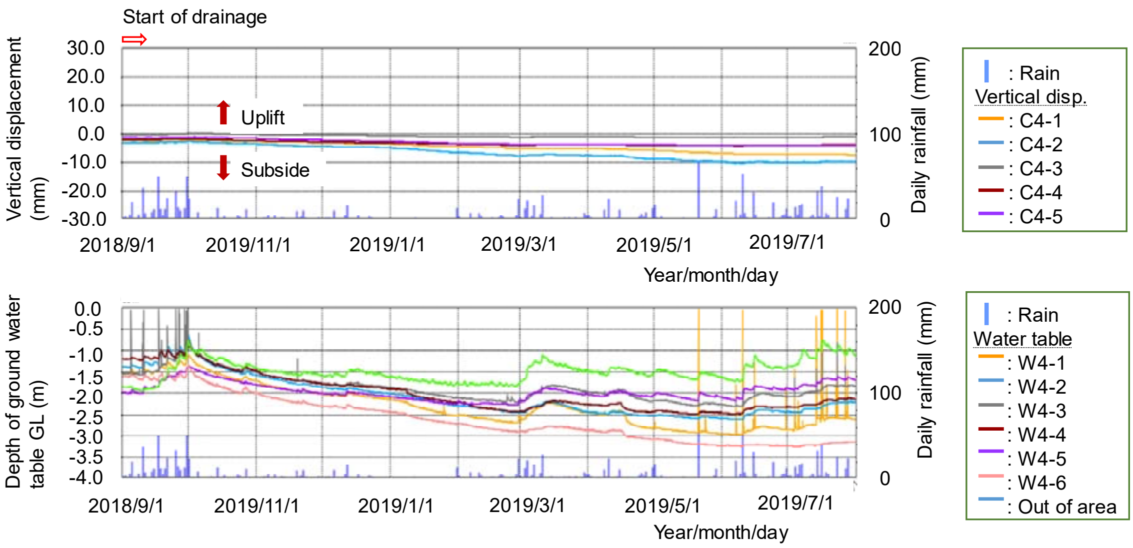
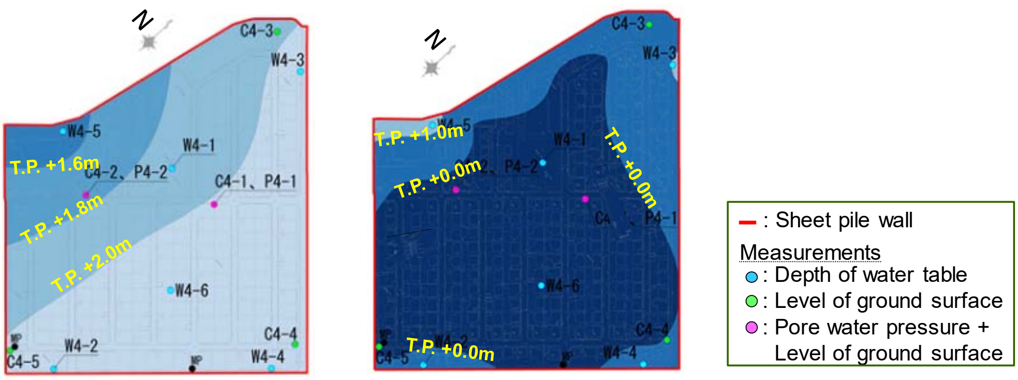


Fig. 23 – Time histories of the ground water level and the settlement of the ground surface in Isobe 4-chome (Chiba City, 2019)



(a) Before drainage (b) 10 month later

Fig. 24 – Distribution of the ground water level in Isobe 4-chome (Chiba City, 2019)

the ground water table occurred just after rains. The settlement of the ground surface due to lowering the ground water level was very small, from 3 mm to 6 mm, less than the settlement during the in-situ test. Figures 24 (a) and 24 (b) show the distribution of the level of the ground water table in the area before drainage and 10 months after drainage had started, respectively. As shown in these figures, the ground water level decreased uniformly in the whole area to T.P. 0 m to +1 m from an original level of T.P. +1.5 m to +2.1 m. Measurements of the ground water level and the settlement of the ground surface continued one more year. However, the level of water table did not change, and the settlement increased only slightly. Finally, the effect of lowering the water level was judged based on Fig. 15. All sites where the ground water level was measured were classified as A, B1, B2 or B3 not C. The total cost of lowering the ground water level in this area was about US $15 million.

Kashima City faces the Pacific Ocean, with sand dunes along the coast. Alluvial lowland and terrace are formed behind the sand dunes. Liquefaction occurred on the coast, in part of the sand dunes, in the filled area on the alluvial lowland and in the filled area on the slope of the terrace, causing serious damage to many wooden houses, roads and lifelines. A technical committee was organized in 2012. Six districts were nominated first, and borings and analyses were conducted. Then, it was decided that three districts, Hirai-tobu, Kashimajingu-ekinishi and Hachigata, would lower the ground water table.

Figure 25 shows the layout of drainage pipes in the Hirai-tobu district. 245 wooden houses existed in

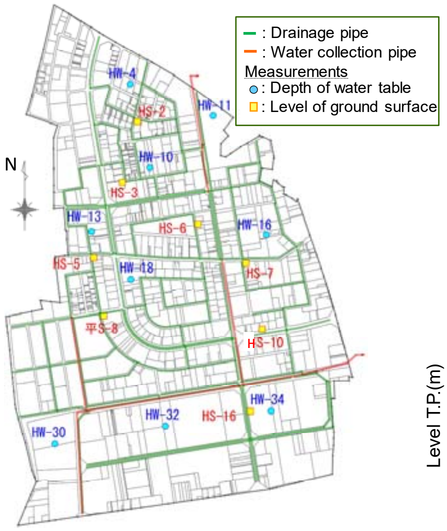


Fig. 25 - Layout of drainage pipes in Hirai-tobu in Kashima City

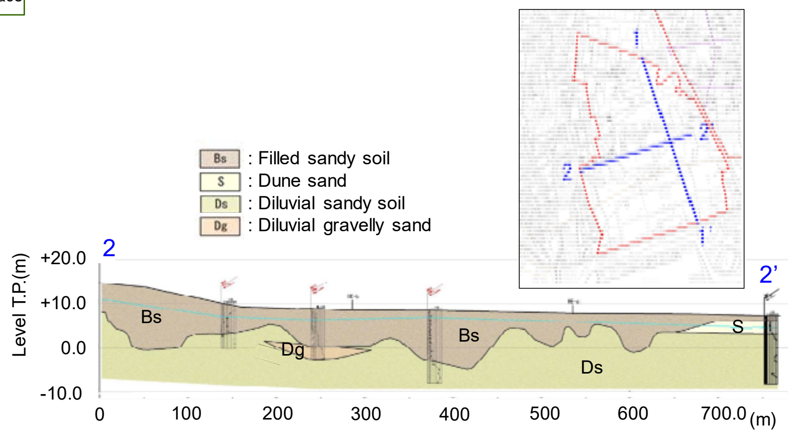


Fig. 26 – Soil cross section from west to east in Hirai-tobu

Fig. 27 – Scattered houses in Hirai-tobu

Fig. 28 – Excavation work in Hirai-tobu

an area of about 68.5 ha. This area is located on sand dunes, and the ground surface slopes gently toward the coast from west to east. As the dune sand is suitable for construction material, it has been extracted and backfilled with other sandy soils at many spots historically. So, as shown in Fig. 26, loose, filled sandy soil is deposited from the ground surface to the depth of 5 m to 15 m, irregularly. A layer of dense, diluvial, gravelly sand lies beneath the sandy soil deposit. The depth of the drainage pipes was designed at a slope of 1 to 48 mm/1000 mm from west to east and with the depth of about 3 m below the ground surface. Drained water flows into water collection pipes, then flowed to ocean naturally. Drainage pipes were constructed by a standard method because wooden houses were being constructed in the area and existing houses were scattered, as shown in Fig.27. First, groundwater level was lowered by well-point method, trenches were excavated, as shown in Fig. 28, then drainage pipes of 200 mm to 300 mm in diameter were placed inside the trenches using permeable sheets and the trenches were backfilled with gravelly sand.

After the construction of the drainage pipes, water drainage started on April 20, 2016. Figure 29 shows the time histories of the ground water level and the settlement of the ground surface, together with the daily rainfall for two years from the start of drainage. The ground water table decreased to about GL-3.0 m to -4.0 m in two years from an original ground water level of GL-0.5 m to -2.0 m. There were few short-time increases in the ground water table due to rainfall. Figures 30 (a) and 30 (b) show the distribution of the level of the ground water table in the area before drainage and two years after drainage, respectively. As shown in these figures, the ground water level decreased to T.P. +4 m to +7 m from an original level of T.P. +6 m to

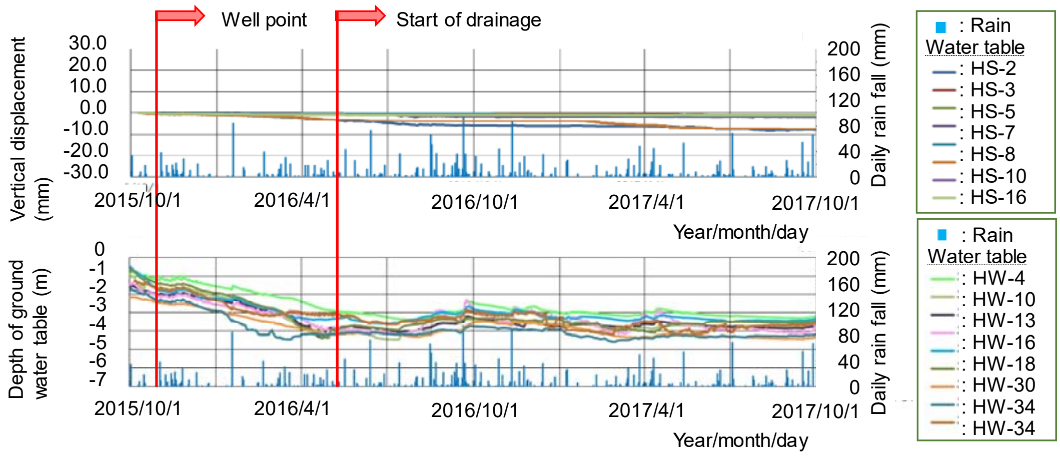


Fig. 29 - Time histories of the ground water level and the settlement of the ground surface in Hirai-tobu

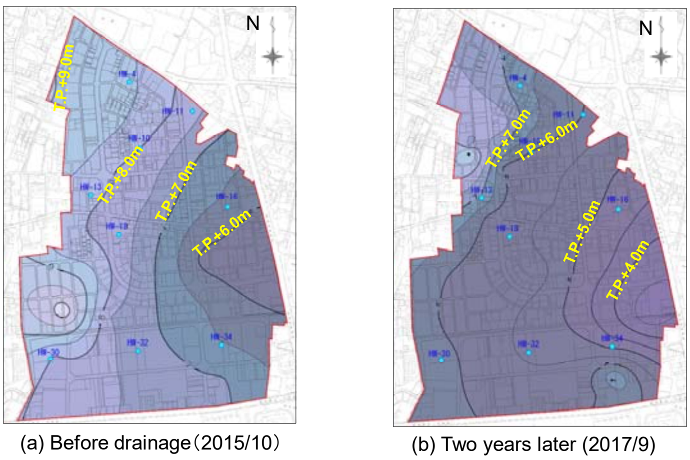


Fig. 30 – Distribution of the ground water level in Hirai-tobu

+9 m, in the whole area. Measurements of the ground water level and the settlement of the ground surface continued for two more years. However, the water table level remained about constant, and settlement increased by only 1 mm. Finally, the effect of lowering of the water level was judged based on Fig. 15. All sites where the ground water level was measured were classified as class A, B1, B2 or B3 not C. The total cost of lowering the ground water level in this area through this method was about US $32 million.

6. Conclusions

After the 2011 Tohoku Earthquake, a new project to protect residential areas against liquefaction was established in Japan. Lowering the ground water table was proposed as a suitable measure and applied to several cities. The process, from in-situ tests to the construction of drainage pipes, is introduced in this paper. The main conclusions obtained from this project are as follows:

(1) Site investigations of damaged and undamaged wooden houses suggested that lowering the ground water table to the depth of 3 m would be effective in preventing liquefaction-induced damage to wooden houses.

(2) In-situ tests showed that the ground settlement due to the lowering of the ground water level to the depth of about 3 m is small, even in soft ground with a soft clay layer. The actual settlement measured in areas where the ground water level decreased was also small.

(3) In the in-situ tests in Chiba City, two rows of drainage pipes were constructed with a distance of about 40 m between them and the water level decreased even in the ground between the two rows. In actual layout in Chiba City, the ground water level decreased uniformly in the measured area.

(4) Lowering the ground water level is effective in countering liquefaction in residential areas where houses are clustered close together and in industrial areas where tanks and warehouses are close together. It is hoped that this method will be applied to such areas before more earthquakes occur.

7. Acknowledgements

Some of the results cited in this paper are quoted from reports by technical committees organized by MLIT, Chiba City, Kashima City and others.

8. References

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