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EFFECT OF THE GROUNDWATER LEVEL ON THE LIQUEFACTION-INDUCED DAMAGE OF WOODEN HOUSE CAUSED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT

During the 2011 Great East Japan Earthquake, many wooden houses were damaged due to liquefaction, although no death was reported. According to Ministry of Land, Infrastructure, Transport and Tourism, about 27,000 houses were damaged due to liquefaction. Since 1974, liquefaction has not been considered while designing wooden houses. In Urayasu City, many houses settled and tilted, although there was no damage to walls and windows. The inhabitants of the highly tilted houses experienced giddiness and nausea and found it difficult to live in their houses after the earthquake.

This study investigated the groundwater level in the residential section of Mihama and Irifune, where serious liquefaction-related damage to wooden houses was confirmed, and evaluated the relationship between groundwater level and damage to wooden houses.

The relationship of groundwater level to the degree of damage to wooden houses was as follows: large-scale half collapsed, −1.1 m; half collapsed, −1.2 m; partially damaged, −1.3 m; and undamaged, −1.7 m, respectively. The groundwater level was the highest in the central part of the reclaimed land and declined gradually toward the sea. The degree of increase in the groundwater level was influenced by a revetment constructed during reclamation. A 0.8-m change in the water table was noticed when comparing the groundwater level between the autumn rain and summer seasons.

According to analysis, when the groundwater level is very shallow (−0.5 m), the criterion for half collapse of the house is not securable. The groundwater level is a damage about half collapse in −1.0 m, No serious damage is caused if the groundwater level is greater than −1.5 m. This analysis result reproduced the result of the field survey well.

INTRODUCTION

The Great East Japan Earthquake, with a magnitude of Mw = 9.0, occurred in the Pacific Ocean, about 130 km off the northeast coast of Japan's main island, on March 11, 2011. Liquefaction occurred in a wide area of reclaimed land along Tokyo Bay, although the distance to the epicenter was very large (about 380 to 400 km). Boiling sands, large settlements, and a kind of sloshing of liquefied grounds were observed in the Tokyo Bay area. According to Yasuda and Ishikawa (2012) and Towhata et al (2012), many houses, roads, lifelines, and river dikes were severely damaged by soil liquefaction. The most seriously damaged area Urayasu City, where about 85 % of the city area experienced liquefaction.

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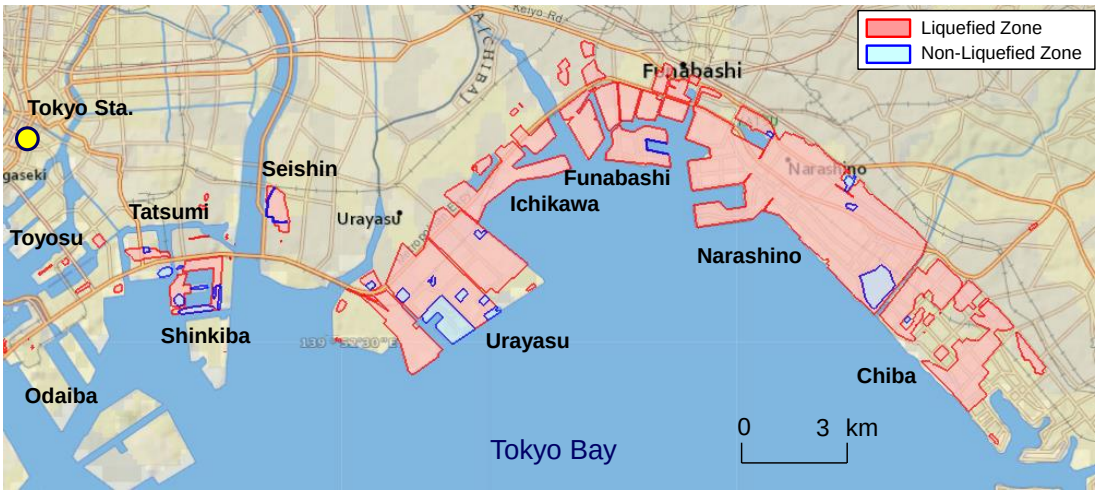

Fig. 1 Liquefied areas from Odaiba in Tokyo to Chiba (MLIT, 2011)

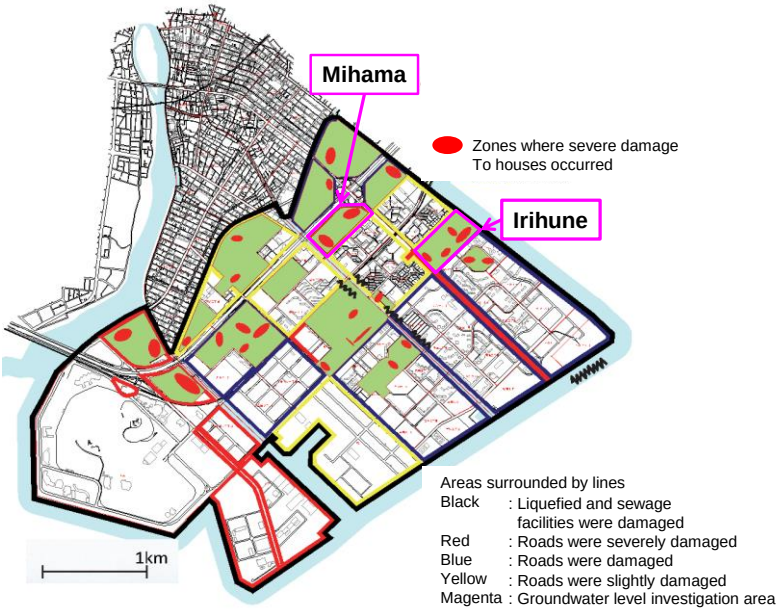

Fig. 2 Zones of Urayasu City where roads, sewage pipes and houses were severely damaged (Urayasu, 2011)

Figure 1 is a map of the liquefied zones in the Tokyo Bay area. Boiling sands were observed in all the reclaimed lands at Shinkiba in Tokyo, Urayasu City, Ichikawa City, Narashino City, and western Chiba City. On the contrary, boiling sands were observed in few of the reclaimed lands at Odaiba, Shinonome, Tatsumi, Toyosu and Seishin in Tokyo, and eastern Chiba City. The total liquefied area from Odaiba to Chiba City was about 41 km^2. Many houses, roads, and lifelines in the liquefied zones were severely damaged.

During the 2011 Great East Japan Earthquake many wooden houses were damaged due to liquefaction, although no death was reported. According to the Ministry of Land, Infrastructure, Transport and Tourism, about 27,000 houses were damaged due to liquefaction. Strip footing foundations or mat foundations are commonly used for houses in Japan. In the design of wooden houses, liquefaction has not been considered, liquefaction since 1974. This is the main reason such a large number of houses were damaged. On the contrary, some houses supported by steel piles or cement-mixed soil piles penetrated to the depth of the not-liquefied layer did not settle.

In Urayasu City, severely damaged houses were located in the zones shown in Fig. 2. Many houses settled and tilted, although there was no damage to walls and windows. Inhabitants of the highly tilted houses experienced giddiness and nausea and found it difficult to live in their houses after the earthquake. In May 2011, the Japanese Cabinet announced a new standard for the evaluation of

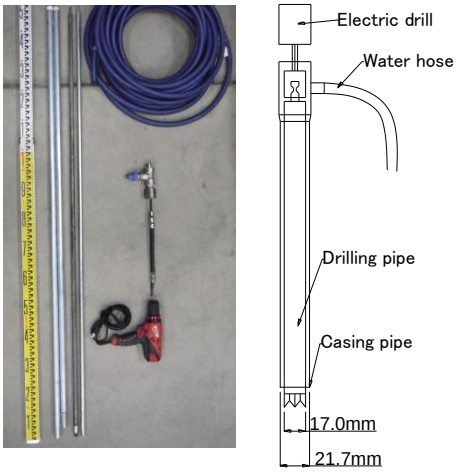

Fig. 3 Instrument for measuring groundwater level

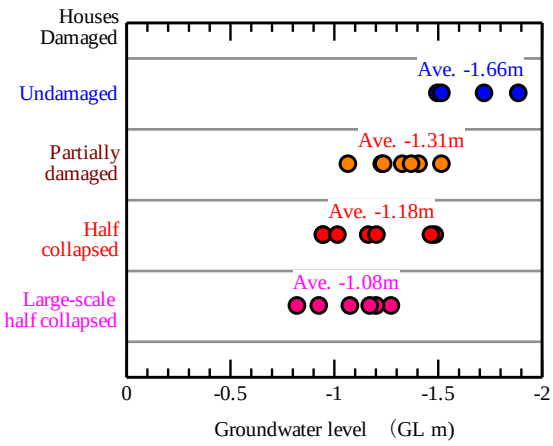

Fig. 4 Relationship between groundwater levels and damage to wooden houses

damage to houses based on two factors, settlement and inclination. A new class of "large-scale half collapsed" was introduced, and houses tilted at angles of more than 1/20, 1/20 to 1/60, and 1/60 to 1/100 were considered to be totally collapsed, large-scale half collapsed, and half collapsed, respectively. The number of totally collapsed, large-scale half collapsed, half collapsed, partially damaged, and undamaged houses in Urayasu City was 14, 1560, 2177, 5267, and 1003, respectively, as of January 6, 2012. According to Yasuda and Ariyama (2008), several factors affect the non-uniform settlement of houses. Among them, the effect of adjacent houses was dominant in the Abehikona housing group. A similar tendency was observed in the Tokyo Bay area. If two houses are close to each other, they tilt toward each other, and if four houses are close together, they tilt toward their center point (Yasuda et al. 2012).

This study investigated groundwater level in the residential section of Mihama and Irihune, where serious liquefaction-related damage to wooden houses was confirmed, and evaluated the relationship between groundwater level and damage to wooden houses.

Groundwater level measurement in a liquefaction-impacted residential area

Groundwater levels were measured in the Irifune and Mihana areas (Fig. 2) from May 2013 to January 2014. A groundwater level measuring instrument (Fig. 3) is portable, hand-powered, and suitable for operation in narrow space. The instrument consists of an electric drill, a hose, a casing pipe, and a drilling pipe. It is a miniature of a boring machine. Groundwater level is measured in the casing after drilling the ground and removing the drilling pipe.

Figure 4 shows the relationship between groundwater levels and damage to wooden houses. The relationship between the groundwater levels and the damage was as follows: Large-scale half collapsed, −1.1 m; half collapsed, −1.2 m; partially damaged, −1.3 m; and undamaged, −1.7 m, respectively. The damage caused to a wooden house tends to be greater when groundwater levels are shallow. In our study, no liquefaction-related damage was confirmed when the groundwater level was greater than −1.5 m. However, groundwater level measurements include the volume compression settlement by liquefaction. The volume compression settlement by liquefaction is about 20 cm (Konagai et al. 2012), and at the time of the earthquake, the groundwater level was about −1.7 m.

Figure 5 shows a map of groundwater level variation in the Irifune area, which was derived from groundwater level measurements of the parks and SWS test results. The groundwater level was higher toward the southeast and lower in the northwest (i.e., seaward). Groundwater level variation was influenced by the revetment created at the time of reclamation. Groundwater levels were highest in the central part of the reclaimed land and were lower in elevation toward the northwest (i.e., seaward). An old revetment on the northeastern side of the area was partially lost. The groundwater level in the park near the end of the old revetment was −1.7 m and was comparatively deeper than that

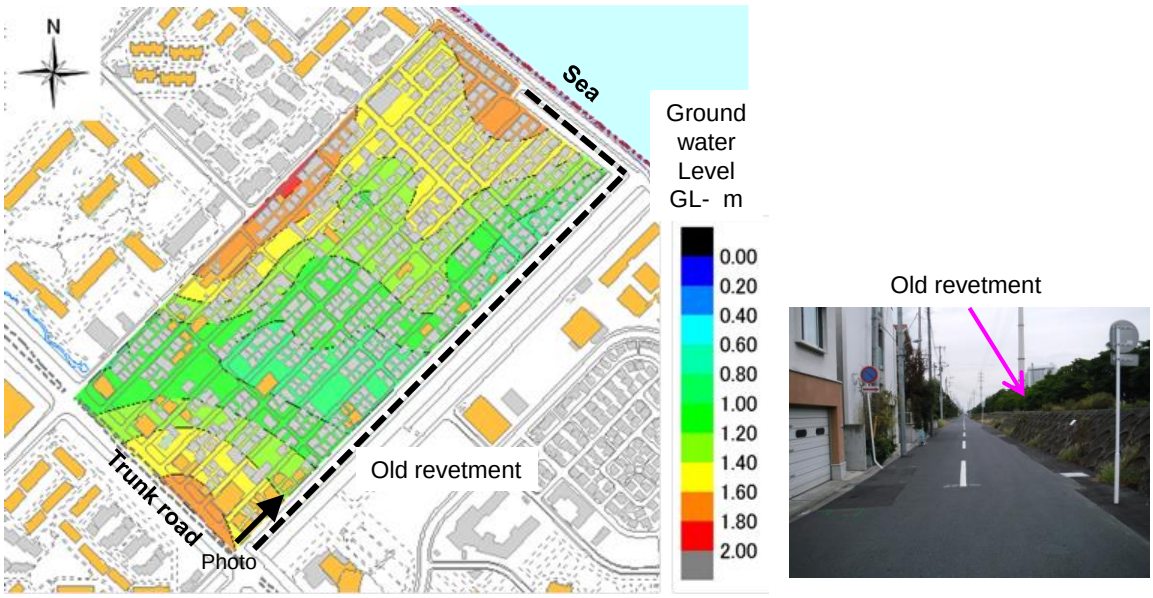

Fig. 5 Groundwater level distribution of Irifune area which used the result of a measurement

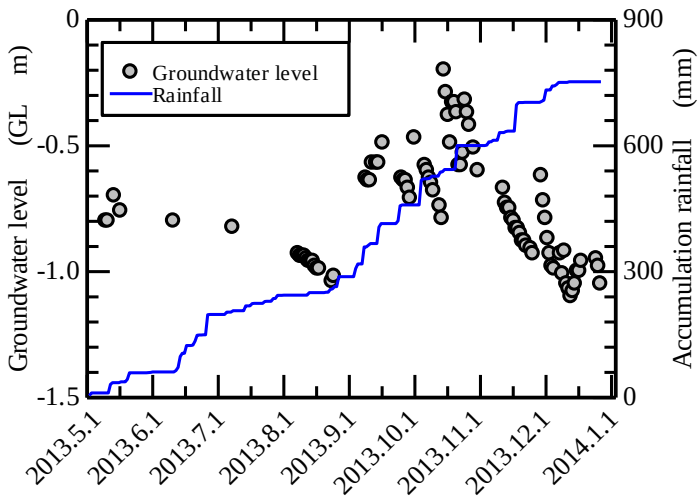

Fig. 6 Season variation of the groundwater level

in the surrounding area. The old revetment was constructed of riprap, covered by concrete blocks, and reinforced on the toe slope with a timber pile and a concrete sheet pile. After the revetment was constructed, the area was reclaimed using a hydraulic dredge, and the area was prepared for habitation. After reclamation, permeability of the area was limited due to clogging of the riprap revetment material. Groundwater level fluctuation beneath the reclaimed land was influenced by the amount of rainfall, infiltration, and tidal level. The seasonal variation in the groundwater level of this area is shown in Fig. 6. The tendency for the groundwater level to change in relation to rainfall was confirmed. The groundwater level in May and June was −0.7 m to −0.8 m. The groundwater level during the summer season in July and August was −0.9 m to −1.0 m. Groundwater levels were very shallow during the autumn rain season September and October, when it was nearly −0.3 m to −0.6 m. After the autumn rain season, the groundwater level dropped to nearly −0.8 m to −1.1 m. Comparison of the groundwater levels during an autumn rain season, a summer season, and a winter season confirmed an approximate change of 0.8 m.

Table 1. Physical-properties of a layer

Layer	N (Time)	γ_t (kN/m^3)	G (kN/m^2)	ν	C (kN/m^2)	ϕ (deg)	R_L	Dr (%)
Fill	10	19.0	1.05E+04	0.33	0.0	35.0	0.315	72
Dredged sand	2	17.0	2.11E+03	0.33	0.0	26.0	0.276	28
Alluvial sand	14	17.5	1.47E+04	0.33	0.0	34.0	0.388	60
Alluvial clay	2	16.0	8.63E+03	0.33	12.5	0.0	-	-
House	-	2.0	1.19E+09	0.33	-	-	-	-

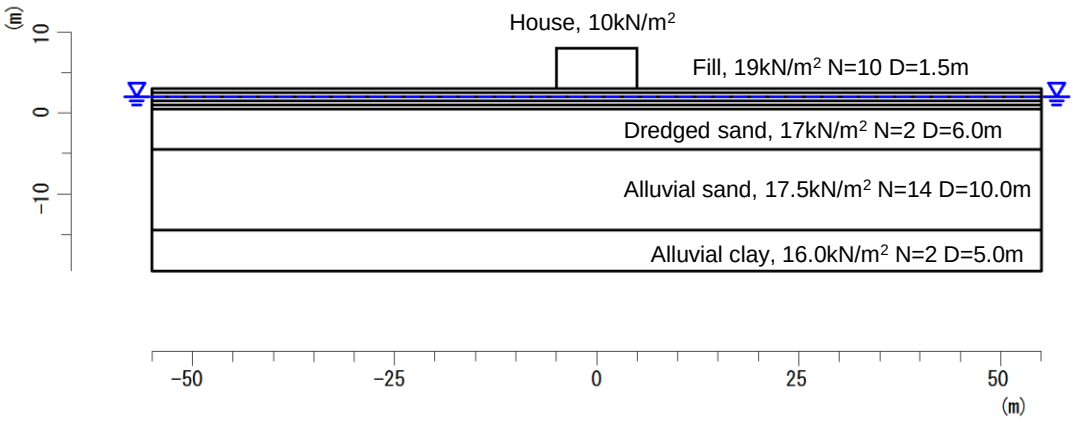

Fig. 7 Model ground and house

Reproduction analysis by a computer code ALID

According to the field survey, damage to wooden houses occurred when groundwater levels were lower than −1.5 m. Settlement and inclination of houses were analyzed using a computer code ALID (Yasuda et al., 1999) to demonstrate the effect of several factors such as groundwater level on the settlment and inclination. The model ground (shown in Fig.7) was modeled from results of the geological survey in the area. The analyses were performed under the conditions shown in Fig. 7. The groundwater model was set up between −0.5 m from −2.5 m using the following factors.

1) Width, height, and pressure of the model houses: 10 m, 5 m, and 10 kN/m^2, respectively

2) Soil layers of the model ground: fill, dredged sand, alluvial sand, and alluvial clay

3) Liquefaction strength ratio (undrained cyclic stress ratio) R_L: 0.315 for fill, 0.276 for dredged sand and 0.388 for alluvial sand

4) Ground surface acceleration: 174.3 gal (same as recorded in Urayasu, Composite acceleration),

5) Correction factor C_w by JRA standard: Cyclic torsional shear test result

The effect of the long duration of the main shock and the aftershock occurred (29 minutes later) was considered by the correction factor C_W, which was derived from cyclic torsional shear tests (Ishikawa and Yasuda, 2013). Table 1 shows the physical-properties of a layer.

In this code “ALID/win,” a finite element method was applied in the following steps:

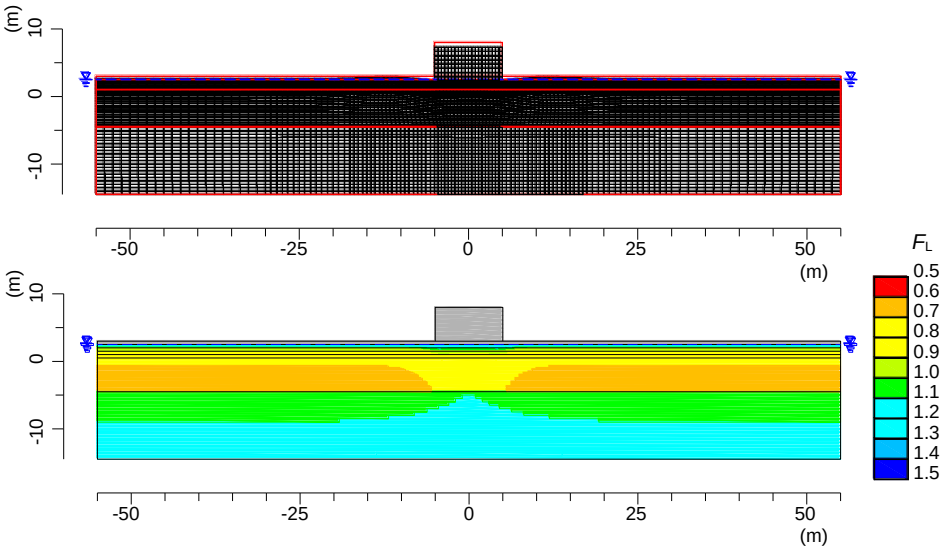

Fig. 8 Deformation of basic case (WL=-0.5m)

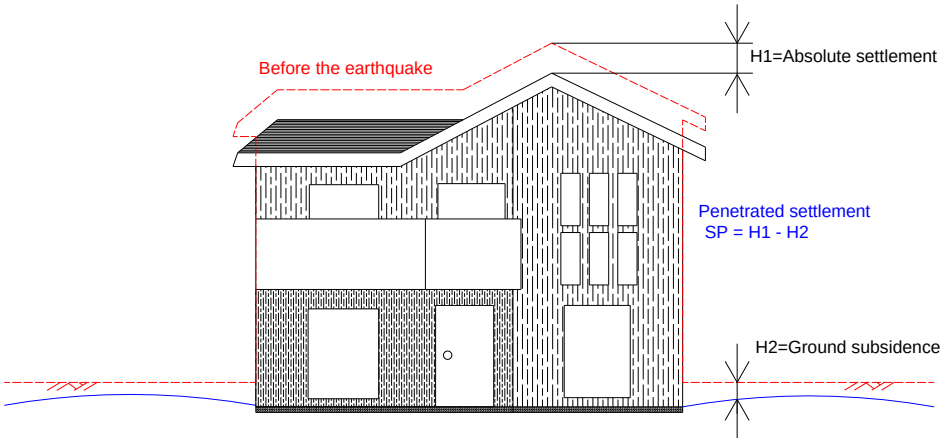

Fig. 9 Deformation of settlement

1) In the first step, the deformation of the ground before the earthquake is calculated by using the stress-strain relationships of non-liquefied soils.

2) The defomation of the ground due to liquefaction is calculated in the second step, by using the stress-strain relationship of liquefied soils.

3) Finally, the deformation of the ground due to the dissipation of excess pore pressure is calculated based on the simple relationships among volumetric strain, F_L and relative density proposed by Ishihara & Yoahimine (1992).

Figure 8 shows the deformation and the distribution of the safety factor against liquefaction. As shown in the deformed meshes, the ground surface subsides and the model house penetrates into the subsided ground. The penetrated settlement (SP), as shown in Fig. 9, is the difference between the absolute settlement of the house and ground subsidence. The F_L values under the house and the surrounding ground are about 0.8 to 1.2 and 0.7 to 1.1, respectively.

A displacement distribution of the ground surface for each groundwater level is shown in Fig. 10. When the groundwater level was −0.5 m, the amount of settlement was about 0.7 m. Meanwhile, when the groundwater level was −2.5 m, the amount of settlement decreased considerably to about 0.15 m. Moreover, when the groundwater level was greater than −2.0 m, the amount of settlement of the house and that of settlement of the ground became comparable. Settlement of the house due to

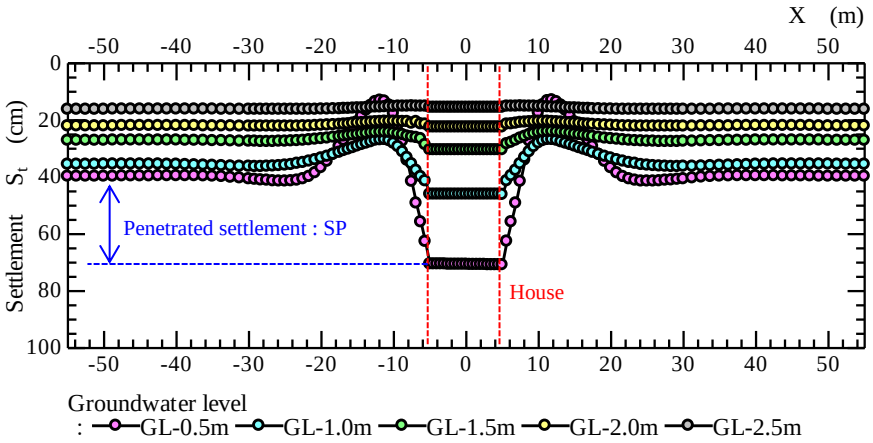

Fig. 10 Displacement distribution of the ground surface to each water level

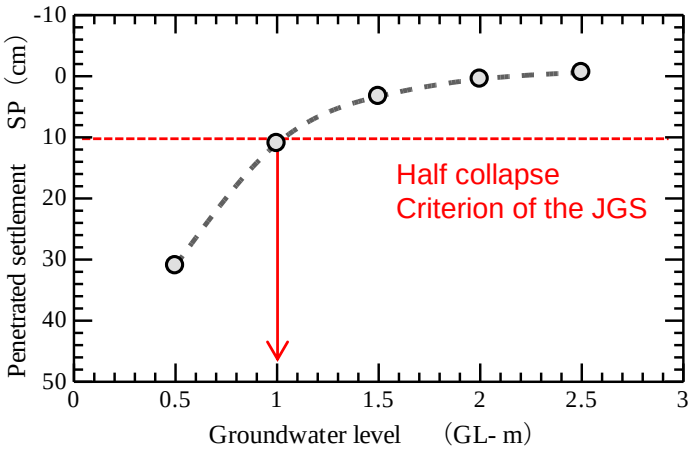

Fig. 11 Relationship between penetration settlement and the groundwater level

liquefaction is strongly subject to the influence of the groundwater level. As a factor of the house setlement due to the difference in the groundwater level, the ground confining pressure increased with decrease in the groundwater level. Therefore, F_L increased because the shear stress ratio decreased as a result of the earthquake, and thus, the distortion of the house became small. Moreover, the ground just under a house subsides because vertical distortion increases in response to the influence of the loading of the house compared with the surroundings ground. Figure 11 shows the relationship between penetration settlement and the groundwater level. The criterion of the Japanese Geotechnical Society determined that the amount of penetrated settlement by the middle earthquake motion was 10 cm for a wooden house. Under this condition, when the groundwater level is very shallow (−0.5 m), the criterion for half collapse of the house is not securable. The groundwater level is a damage about half collapse in −1.0 m, No serious damage is caused if the groundwater level is greater than −1.5 m. This analysis result reproduced the result of the field survey well.

CONCLUSIONS

This study involved groundwater measurement in Urayasu, which suffered damage caused by liquefaction by the Great East Japan Earthquake and evaluation of the relationship between damage to wooden houses and the groundwater level.

1. The relationship of groundwater level (GL) to the degree of damage to wooden houses was as follows: large-scale half collapsed, −1.1 m; half collapsed, −1.2 m; partially damaged, −1.3 m; and undamaged, −1.7 m, respectively.

2. The groundwater level was the highest in the central part of the reclaimed land and declined gradually toward the sea. The degree of increase in the groundwater level was influenced by a revetment constructed during reclamation. A 0.8-m change in the water table was noticed when comparing the groundwater level between the autumn rain and summer seasons.
3. According to analysis, when the groundwater level is very shallow (−0.5 m), the criterion for half collapse of the house is not securable. The groundwater level is greater than −1.5 m.

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