Damage to houses in Urayasu due to liquefaction by the Tohoku-Pacific Ocean earthquake

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SUMMARY
On 11 March 2011 The Tohoku-Pacific Ocean earthquake caused wide and severe liquefaction in the reclaimed lands along Tokyo Bay in Japan. Urayasu is the most severely damaged city where many houses settled and tilted resulting in the problem for inhabitants to live in the damaged houses because they feel giddy and nausea. In Tokyo Bay area, the very long duration of the main shock and an aftershock 29 minutes later probably caused serious settlement and inclination of houses. Many inhabitants are facing to the serious problem how to restore the damaged houses. Complicated problem is the re-liquefaction during aftershocks or future earthquakes. The best way is to improve the ground under houses by compaction or other methods. The authors conducted several analyses to demonstrate appropriate depth of the compaction zone and concluded that about 3 m of depth may be enough to prevent obvious settlement.

Keywords: Liquefaction, house, settlement, countermeasure

1. INTRODUCTION

Many houses have been damaged due to liquefaction during previous earthquake in Japan. However, actual damage to inhabitants has not been highlighted up to the 2000 Tottoriken-seibu earthquake which caused severe settlement of numerous timber houses in two housing lots. Of them, about 100 houses settled and tilted at Abehikona housing lot in Yonago City (Yasuda et al., 2004, Yasuda and Ariyama, 2008). The area of the housing development is almost a square of 360 m x 360 m. 169 timber houses with mainly two stories had been constructed before the 2000 Tottoriken-seibu earthquake. Of them 116 houses settled and tilted though no severe cracks were observed on the walls of the settled houses. As more than 100 houses settled and tilted due to liquefaction, angles of inclination of the settled houses were measured after the earthquake. In the heavily tilted houses, inhabitants felt giddy and nausea, and could not live in their houses after the earthquake, though walls, pillars and windows of the houses had no damage. Heavily tilted houses had to be restored to horizontal. In the restoration work, super-structures were uplifted by jacks, footings were repaired or reconstructed to become horizontal, and then the superstructures were replaced on the footings. The cost of the restoration work for one house was about three to four million Yen (about US$ 25,000 to 35,000).

After the Tottoriken-seibu earthquake, the 2003 Tokachi-oki, the 2004 Niigataken-chuetu and the 2007 Niigataken-chuetsu-oki earthquakes caused liquefaction-induced damage to houses. However few attentions have been paid up to the 2011 Tohoku-Pacific Ocean earthquake because numbers of damaged houses have been not large.

2. SETTLEMENT AND INCLINATION OF HOUSES IN URAYASU DURING THE 2011 TOHOKU-PACIFIC OCEAN EARTHQUAKE

The 2011 Tohoku-Pacific Ocean earthquake (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. According to the result of totaling by the Ministry of Land, Infrastructure, Transport and Tourism, about 27,000 houses were damaged due to liquefaction. About a half of the damaged houses are located in Tokyo Bay area as shown in Figure 1. Total area of liquefied zones in the Tokyo Bay area, from Shinkiba in Tokyo through Urayasu, Ichikawa and Narashino cities to Chiba City was about 41km^2. Most severely damaged city was Urayasu City. Figures 2(1) and 2(2) show liquefaction-induced damage taken one day after the earthquake. Much water and sands spewed out, many houses settled and tilted, electric poles settled and roads were waved or heaved. Figures 3 (1) and 3 (2) show a damaged house in Urayasu taken from outside and inside, respectively. Though no damage to walls and windows were observed, the house settled and tilted about 40/1,000. Large settlement which means the penetration of houses to the ground, such as 30 cm caused damage to water, sewage water and gas pipe by tearing or bending. Moreover, in the heavily tilted houses, inhabitants feel giddy and nausea, and difficult to live in their houses after the earthquake as recognized at Abehikona housing lot during the 2000 Tottoriken-seibu earthquake mentioned above. Then, on May, Japanese Cabinet announced new evaluation standard for the damage of houses by the two factors, settlement and inclination, as shown in Table 1. New class "large-scale partially destroyed house" was also introduced, and tilted houses more than 1/20, 1/20 to 1/60, 1/60 to 1/100 are judged as completely destroyed, large-scale partially destroyed, and partially destroyed houses, respectively in the standard. Numbers of damaged houses in Urayasu City by the new standard are listed in Table 2 together with the numbers counted by old judging method (Urayasu City, 2011). Numbers of completely and partially destroyed houses increased drastically, and the numbers of damaged houses more severe than partially destroyed enlarged to 3680.

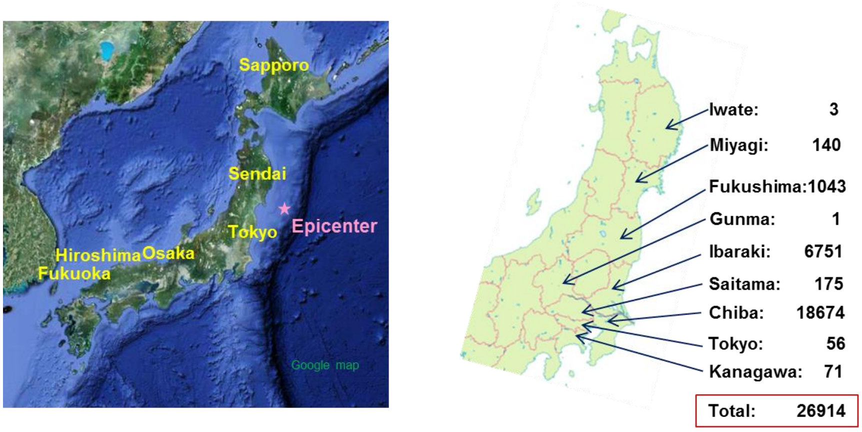

Figure 1. Numbers of the damaged houses due to liquefaction in each prefecture during the 2011 Tohoku-Pacific Ocean earthquake

Figure 2 (1) to (2). Damage in Urayasu City in the next day

(1) Outside of the tilted house (2) Inside of the tilted house

Figure 3. Severely settled and tilted house in Urayasu City

Table 1. New evaluation standard for the damage of houses

Grade of damage	Evaluation method	
	Inclination	Settlement
Completely destroyed	More than 1/20	Floor to 1m upper htan floor
Large-scale partially destroyed	1/60 to 1/20	25cm upper than footing to floor
Partially destroyed	1/100 to1/60	Up to 25cm upper than footing

Table 2. Numbers of damaged houses in Urayasu City by old and new standard (Urayasu City)

Grade of damage	Number of houses	
	Old standard	New standard
Completely destroyed	8	18
Large-scale partially destroyed	0	1,541
Partially destroyed	33	2,121
Partially injured	7,930	5,096
No damage	1,028	1,105
Total	8,999	9,881

3. EFFECT OF LONG DURATION OF MAIN SHOCK AND A BIG AFTERSHCK ON THE LIQUEFACTION-INDUCE DAMAGE TO HOUSES

Many seismic records were obtained in Tokyo Bay area the 2011 Tohoku-Pacific Ocean earthquake. Among them, accelerographs recorded at K-NET Inage in Chiba where actually boiled sand was observed is shown in Figure 4 together with that at K-NET Urayasu which was recorded on the ground in where liquefaction did not occur. Both records started almost same time; 14:46:16 at Inage and 14:46:15 at Urayasu. In Urayasu's wave frequency did not change drastically after the peak acceleration which induced at about 118 sec. (14:48:13). On the contrary frequency changed to low value after two peaks at 120 sec. (14:48:16) and 126 sec. (14:48:22). Therefore it can be judged liquefaction occurred at around 14:48:16 to 14:48:22 at K-NET Inage. This means many cycles of shear stress, say around 20 cycles from 110 sec. might cause liquefaction at K-NET Inage site. And it must be noted shaking still continued for long time after the occurrence of liquefaction. One more impact to the ground must be the shaking by the aftershock which occurred 29 minutes later. Peak horizontal accelerations composited from NS and EW components during main shock and aftershock at 6 K-NET sites are indicated in Figure 5. The peak accelerations during the aftershock were almost a half of those during the main shock in Tokyo Bay area.

The author sent out questionnaires to about 30 inhabitants to ask the timing of boiling and height of boiled muddy water. Answers are summarized in Figure 6. About 1/3 persons observed the boiling of muddy water immediately after the main shock, however another 1/3 persons recognized the spout of muddy water 5 to 9 minutes after the main shock. Other persons found the muddy water at different timing. Height of the muddy water was not high as mainly less than 9 cm after the main shock. About 2/3 persons mentioned that the boiling of muddy water continued up to the aftershock, and about 3/4 persons watched covered water until aftershock. On the contrary, about 3/4 persons observed spew out of muddy water just after the aftershock and the height of the water was apparently greater than the height after the main shock. This means the boiling accelerated due to the aftershock and more severe liquefaction occurred during aftershock at some sites. Question on the timing of the settlement of houses must be difficult to answer for inhabitants, however, a 1/3 persons and another 1/3 persons answered that the settlement of their houses was zero and 10 to 19 cm, respectively after the main shock. And, many inhabitants recognized the settlement on the next day.

Therefor it seems a part of houses settled during or immediately after the main shock though other houses settled after the aftershock. The houses settled during main shock might settle more during after shock. As mentioned above many persons watched covered water until aftershock. Then, settlement of houses is excitable during the aftershock though shaking amplitude was less than that during the main shock as schematically shown in Figure 7.

Now many inhabitants are facing to the serious problem how to restore the damaged houses. Complicated problem is the re-liquefaction during aftershocks or future earthquakes. Not only the restoration but also some countermeasure against re-liquefaction must be applied, but the problem is the cost and the technique to treat the ground under existing structures. Then early development on effective and economic measures against liquefaction for existing timber houses are facilitating by several organizations. Moreover, applicability of special measures to improve an area by decreasing ground water table is studying.

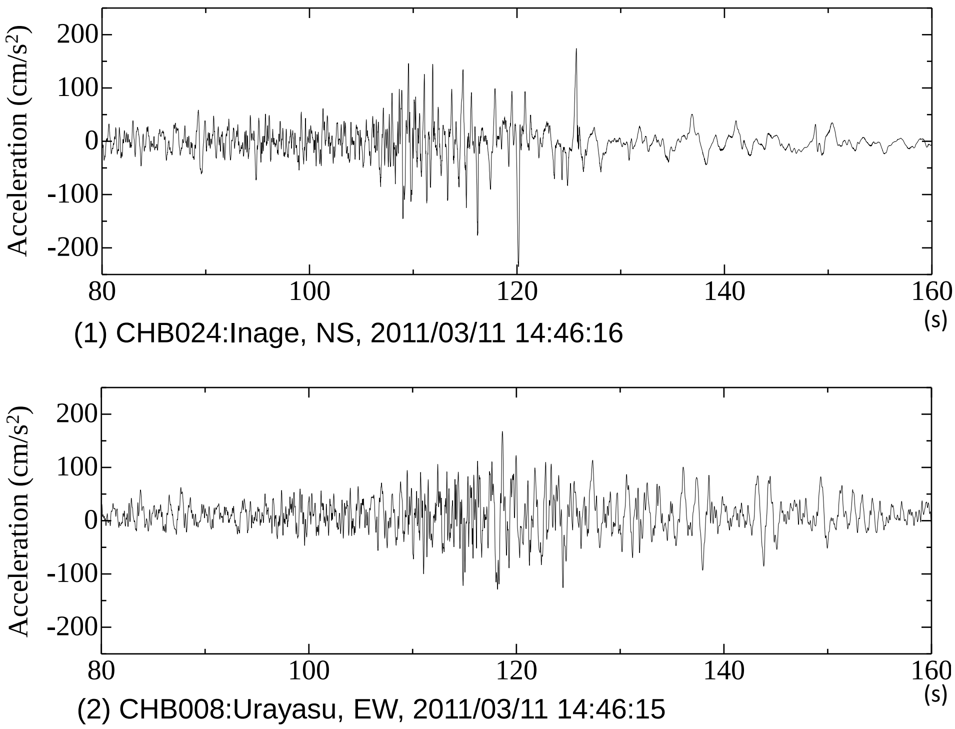

Figure 4. Comparison of accelerographs recorded at K-NET Inage and Urayasu

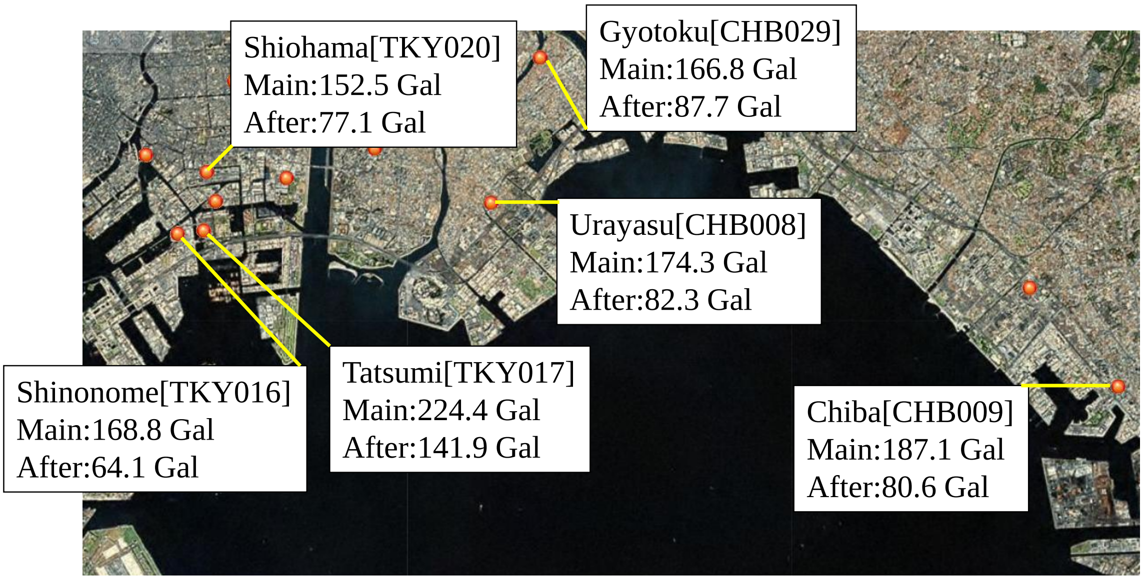

Figure 5. Comparison of accelerations during main and aftershocks by K-NET

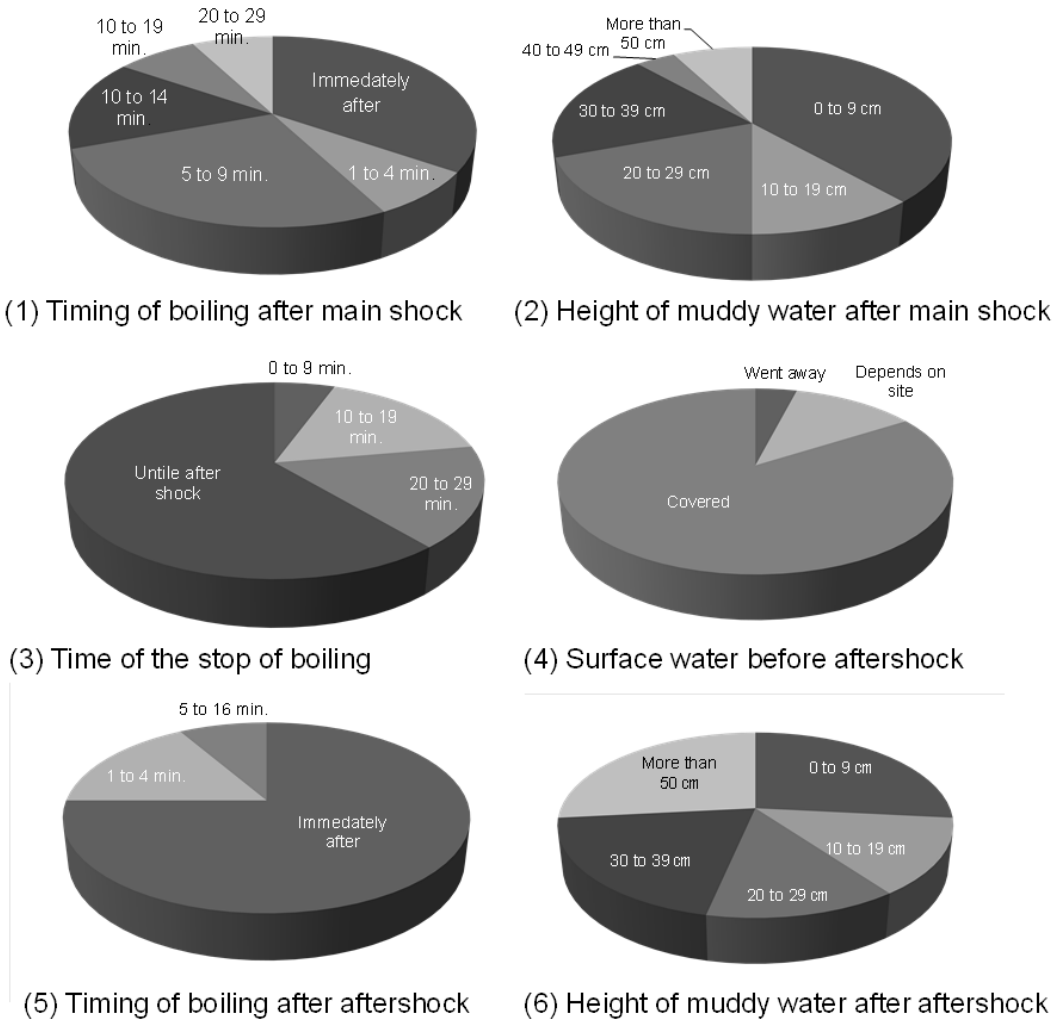

Figure 6. Questionnaires to inhabitants in Irifune

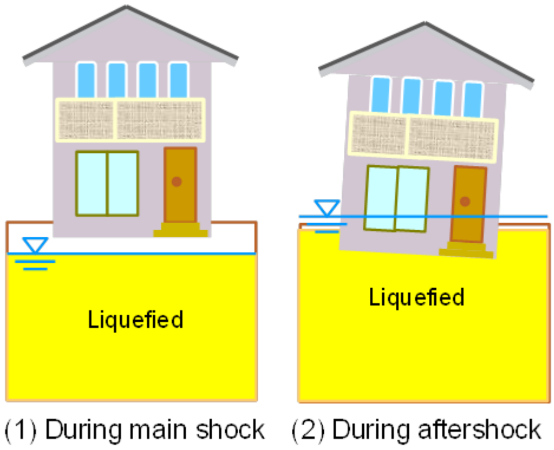

Figure 7. Possible effect of aftershock on the settlement of house

4. ANALYSES FOR LIQUEFACTION-INDUCED DIFFERENTIAL SETTLEMENT

After the damage by the 2000 Tottoriken-seibu earthquake, the authors had tried to analyse the settlement and inclination of houses by a computer code ALID (Yasuda et al., 1999) to demonstrate the effect of several factors such as depth of water level on the settlement and the inclination (Yasuda and Ariyama, 2008). Then, in this study, the authors conducted several analyses to demonstrate the effect of aftershock on the settlement and appropriate countermeasure methods. The analyses were carried out under the following conditions for a model ground and a model house shown in Figure 8. Compaction of the ground by compaction grouting or other methods under the house was assumed as the countermeasure.

1) Width, height, pressure of the model house: 12.5m, 5.0 and 9.81kN/m^2, respectively,
2) Soil layers of the model ground: fill, dredged sand and alluvial sand, alluvial clay,
3) Liquefaction strength ratio (undrained cyclic stress ratio) R_L: 0.297 for fill, 0.281 for dredged sand and 0.365 for alluvial sand,
4) Depth of ground water table: WL=0m
5) Ground surface acceleration: 157.3gal (same as recorded in Urayasu, EW direction),
6) Correction factor C_w by JRA standard: 0.82
7) Depth of compacted zone: GL-1.0m, GL-2.0m and GL-3.0m,
8) Outside area of compacted zone: 1.0 m outside from model house,
9) SPT N-value of compacted zone: 12,

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 (Yasuda, Ishikawa and Hagiya, 2012).

Figure 9 shows the deformation together with the distribution of safety factor against liquefaction, F_L for the case without compaction. As show in the deformed meshes, the ground surface subsides and the model house penetrates in the subsided ground. Then, penetrated settlement S_P is defined as shown in Figure 10, because the penetrated settlement is more important than absolute settlement of the house and ground subsidence. The F_L values under the house and surrounding ground are about 0.8 to 1.0 and 0.7 to 0.8, respectively. On the contrary, analysed result for the case compacted up to the depth of 3.0 m is shown in Figure 11. In this case the F_L values in the compacted zone increase to more than 1.5 which means not liquefied and no obvious penetrating settlement occurs. The penetrated settlement, absolute settlement and ground subsidence are plotted with the depth of compacted zone in Figure 12. The penetrated settlement without countermeasure is 12.1 cm and decreases with the depth of the compacted zone.

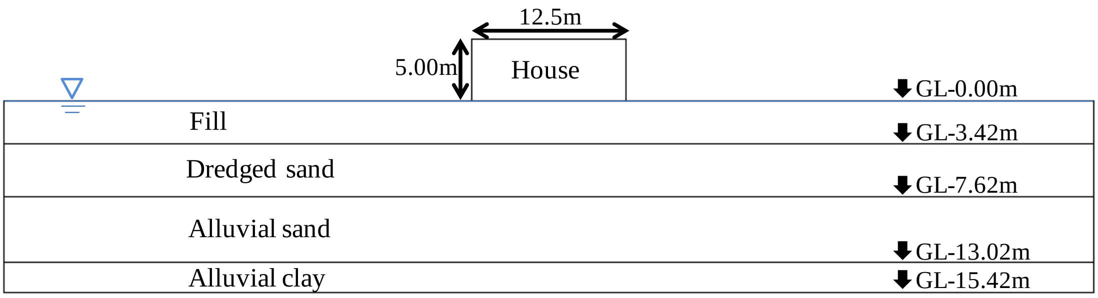

Figure 8. Model ground and house

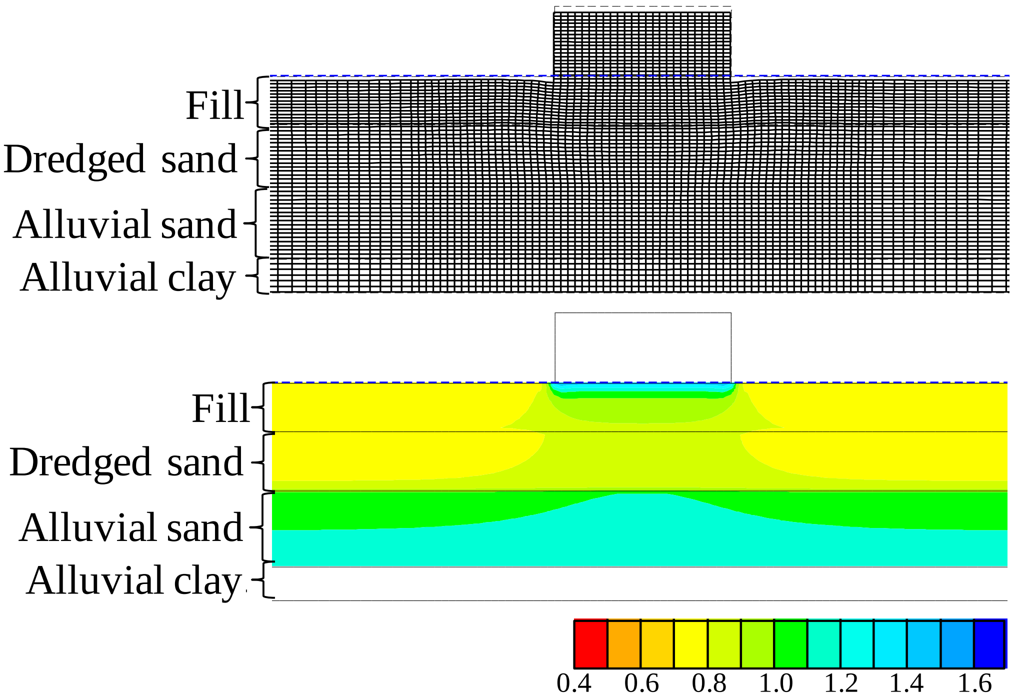

Figure 9. Deformation of basic case (WL= 0m, without compaction)

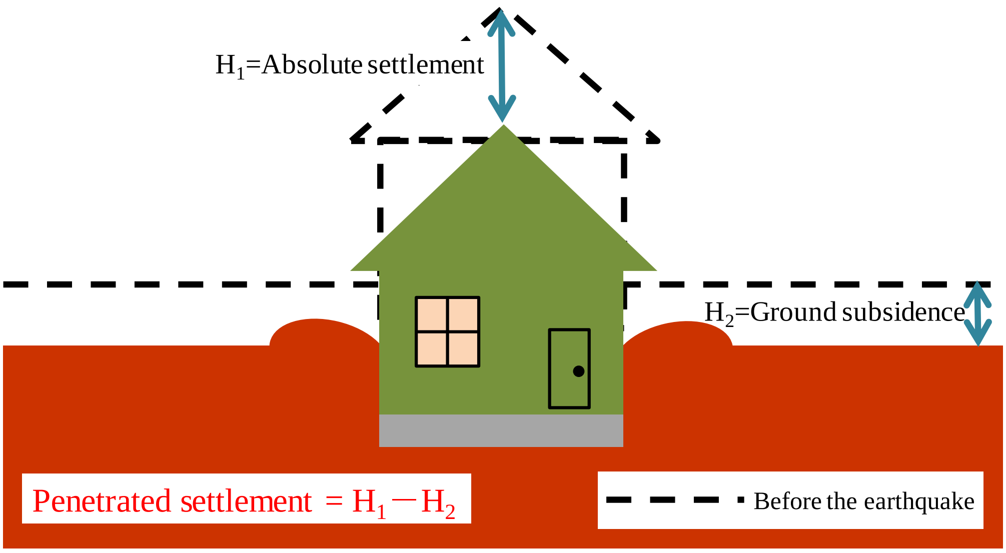

Figure 10. Definition of settlement

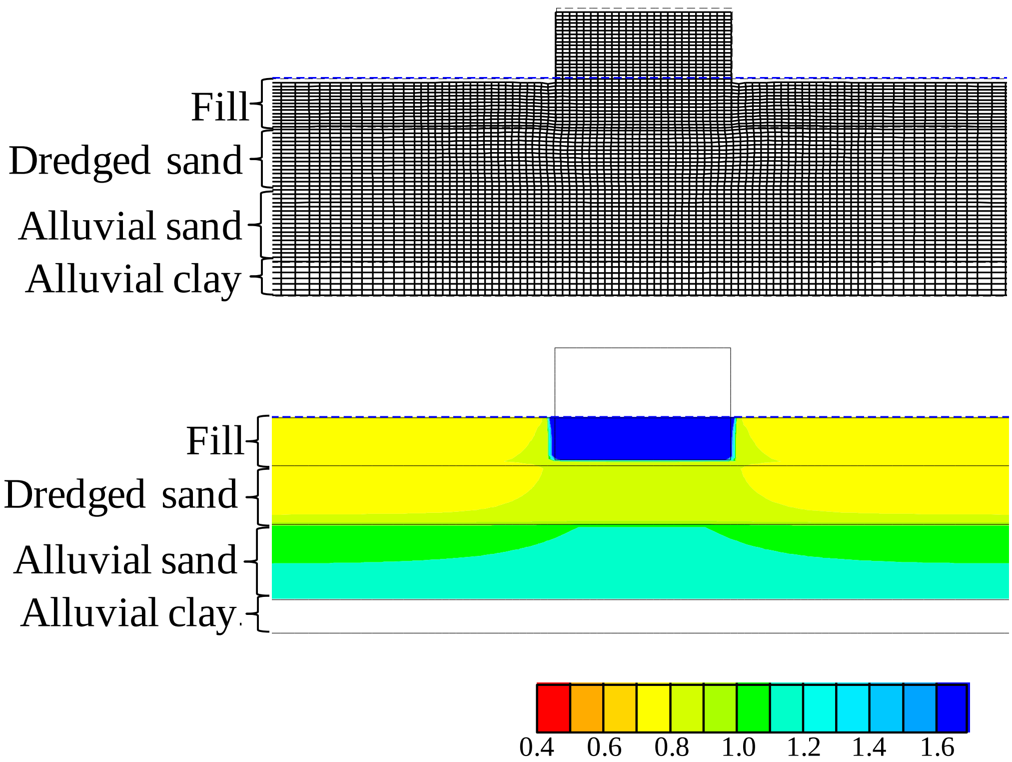

Figure 11. Deformation of basic case (WL= 0m, Compacted up to the depth of 3.0 m)

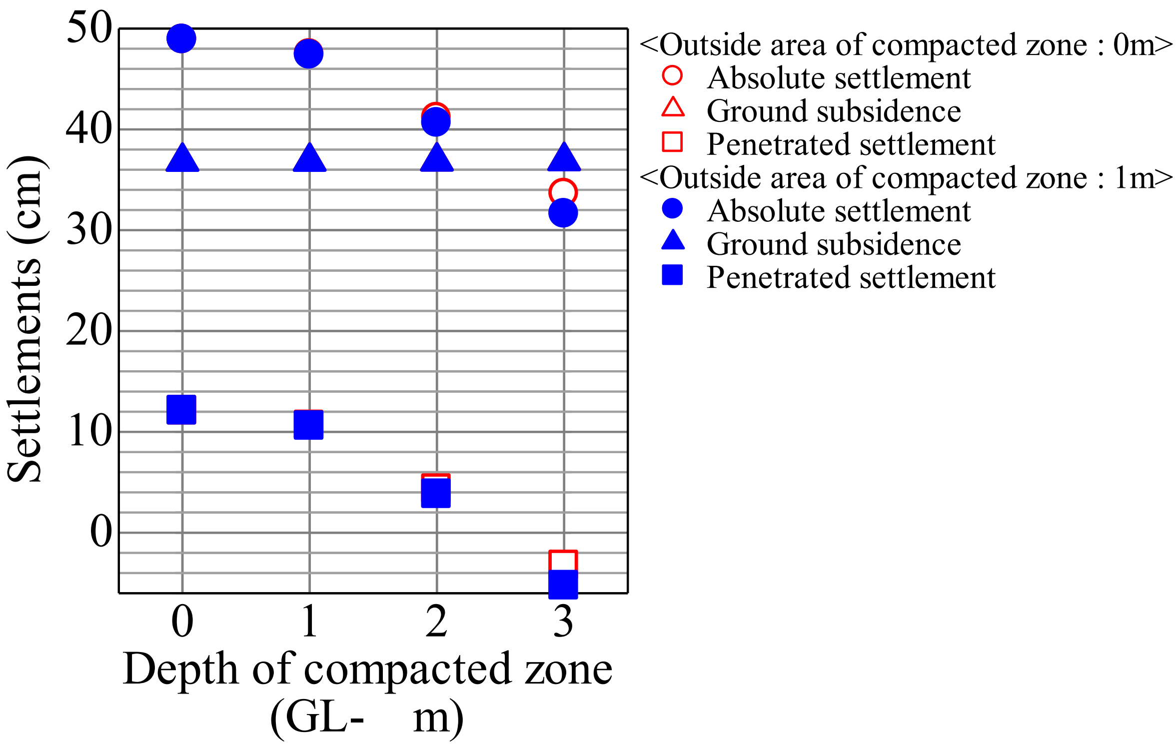

Figure 12. Relationship between depth of compacted zone and settlements

5. CONCLUSIONS

The authors conducted site survey and analyses on the liquefaction-induced settlement of houses in and around Urayasu City during the 2011 Tohoku-Pacific Ocean earthquake and the following conclusions were derived:

1. Very long duration of the main shock and an aftershock 29 minutes later probably caused serious settlement and inclination of houses.
2. Settlement must be prevented by compacting the ground in some depth, say about 3 m under houses. But more studies are necessary.

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