

SEVERAL FEATURES OF LIQUEFACTION-INDUCED DAMAGE TO HOUSES AND BURIED LIFELINES DURING THE 2011 GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: The 2011 Great East Japan earthquake caused severe liquefaction in Tohoku and Kanto districts. About 27,000 timber houses, a lot of buried sewage pipes and roads were damaged due to liquefaction. In Tokyo Bay area, the very long duration of the main shock and an aftershock 29 minutes later probably induced the severe liquefaction. Sidewalks and alleys buckled at several sites, probably due to a kind of sloshing of liquefied ground. Moreover, much sand boiled from the ground and the ground subsided significantly because the liquefied soils were very fine.

Key Words: Great East Japan earthquake, liquefaction, house, sewage pipe, road

INTRODUCTION

The 2011 Great East Japan Earthquake, with a magnitude of $M_w=9.0$ 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, though the epicentral distance was very large, about 380 to 400 km. Much land has been reclaimed in the Tokyo Bay area since the seventeenth century. Liquefaction has been induced during past earthquakes, such as 1923 Kanto Earthquake and 1987 Chibake-toho-oki Earthquake. However, the Great East Japan Earthquake is the first on record to cause liquefaction in such a wide area and to severely damage houses, lifelines and roads. In this paper, the authors focus on the liquefaction-induced damage in Tokyo Bay area.

INVESTIGATION OF LIQUEFIED SITES

The authors started to investigate Tokyo Bay area on the next day from the earthquake because all train in Tokyo Bay area stopped service immediately after the earthquake until the midnight of the day. In the investigation the roads where boiled sands were observed and not observed, were marked on maps as shown in Figures 1. The zones surround by red lines were judged to be liquefied, but, note is necessary

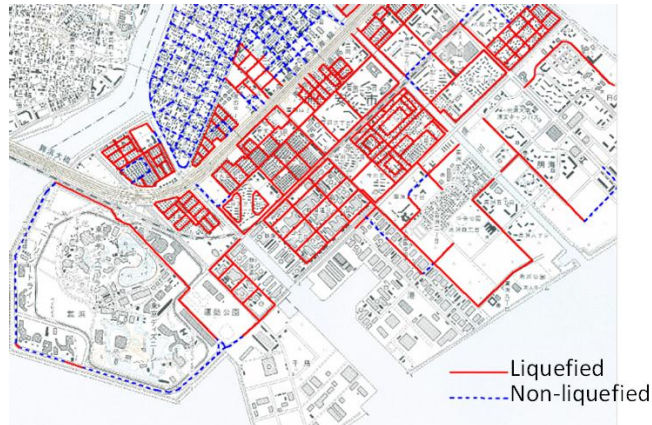


Figure 1 Method to judge liquefied and non-liquefied zone (Yasuda et al., 2011)

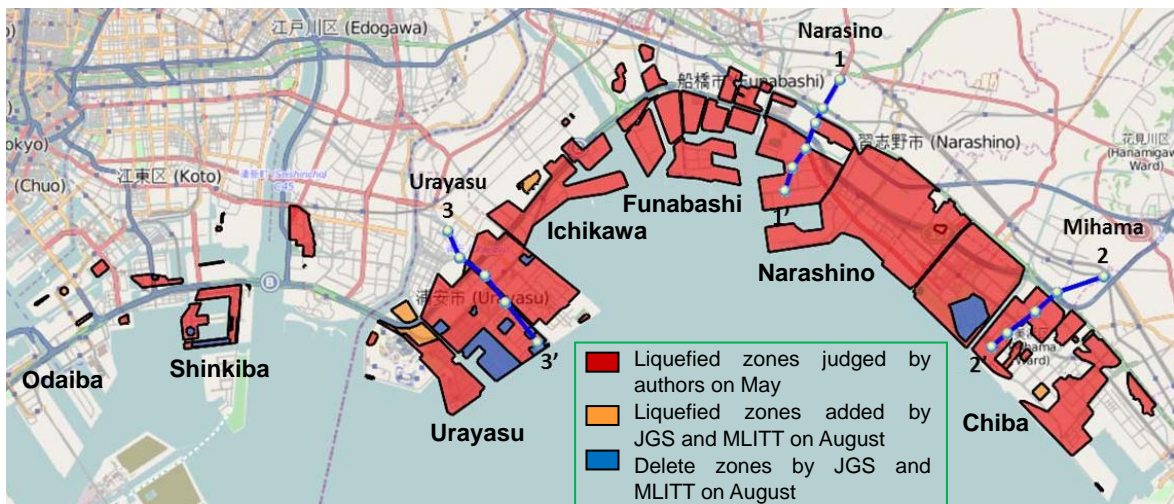


Figure 2 Liquefied area from Odaiba in Tokyo to Chiba City (Joint research by Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism and JGS)

that some small districts in the zones did not liquefy because their grounds had been improved by sand compaction method or other methods mentioned later. Thus about ten days were necessary to investigate the whole area from Odaiba in Tokyo to Chiba City through Urayasu, Ichikawa and Narashino Cities. A tentative map of liquefied zones was drawn based on this first stage investigation (Yasuda and Harada, 2011).

As the liquefaction-induced damage to houses, river dikes, roads, lifelines and ports and harbors were serious, Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism, intended to make joint research with JGS to identify liquefied sites. Figure 2 is the map of liquefied zones thus estimated which is slightly modified from the tentative map.

SOIL CONDITION IN LIQUEFIED AREA

As demonstrate in Figure 2, severely liquefied area by the earthquake was from Shinkiba in Tokyo to Chiba City through Urayasu, Ichikawa, Funabashi and Narashino Cities in Chiba Prefecture. The reclaimed lands in this area were constructed after 1966. In the reclamation work dredged soils were filled from the bottom of sea to the height of about sea level. Then the filled surface was covered with hill sands. Figure 3 draws the process of the dredging work. The soils of sea bottom were excavated by a cutter, exhausted with water by a pump, transported by a convey pipe then discharged from the exit of

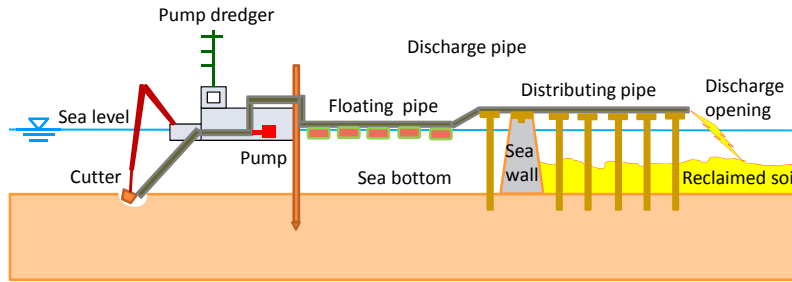


Figure 3 Process of dredging work

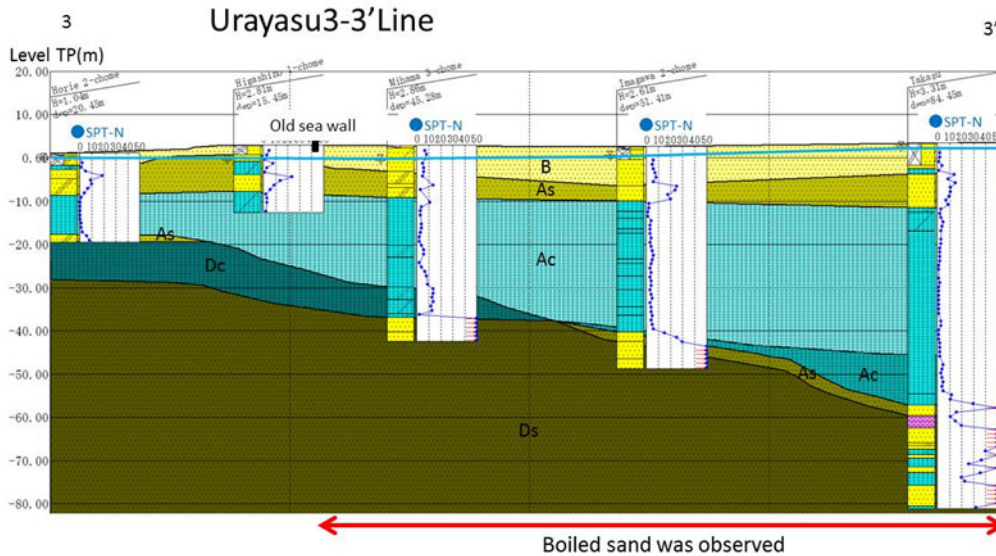


Figure 4 Estimated brief soil cross sections

the pipe. As the dredged soils contain much water, coarse soil grains and fine soil grains are apt to deposit near the exit and far from the exit, respectively. Moreover the position of the exit moves to various positions, resulting in very non homogeneous strata. After filling with the dredged soils and covered by the hill sands, no soil improvement works were treated except several special areas where sand compaction piles or gravel drain piles and other methods were applied to prevent liquefaction.

As three sets of data base had been published by JGS, Chiba Prefecture and Tokyo Metropolitan in the liquefied area, the authors estimated brief soil cross sections along 11 lines which are perpendicular to the shore lines based on these data. Figure 4 illustrate the estimated soil cross sections along a line in Urayasu 3-3' together with the zones where sand boils were observed. The zones where sand boils were observed are exactly coincided with the area of reclaimed land which is the sea side from old sea wall. In the reclaimed zone, a filled layer with mainly hill sand (B) and a filled layer by dredged sandy soil (F) with low SPT *N*-values of 2 to 8 are deposited with a thickness of 6 to 9 m. An alluvial sand layer (A_s) with SPT *N*-values of 10 to 20 underlay with a thickness of 4 to 8 m. A very soft alluvial clay layer (Ac) is deposited under the A_s layer with a thickness of 10 to 40 m, by increasing the thickness towards sea. Diluvial dense sandy layer (Ds) with SPT *N*-value more than 50 underlay. Water table is shallow as GL -0.5 m to -3 m, by decreasing the depth towards sea. On the contrary, in the zone where sand boil was not observed, A_s layer deposited from ground surface. Therefore it can be estimated that the A_s layer basically did not liquefy by the 2011 Great East Japan earthquake though some loose part might liquefy in the reclaimed land, and that some part of the dredged sandy soil under water table might liquefied. Composition of soil layers is similar in other 10 soil cross sections, though thickness of each layer is different.

A technical committee organized by Urayasu City Government and chaired Prof. K. Ishihara carried

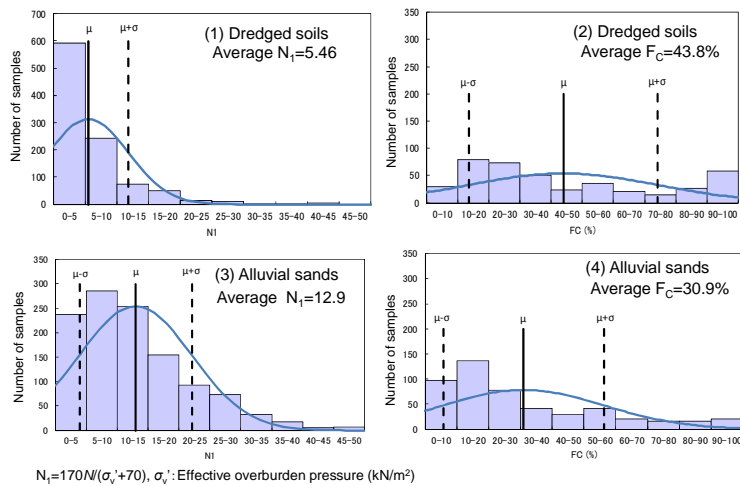


Figure 5 Frequency distributions of N_1 and F_c for dredged soils and alluvial sands (Quoted from the research material by the Technical Committee organized by Urayasu City)

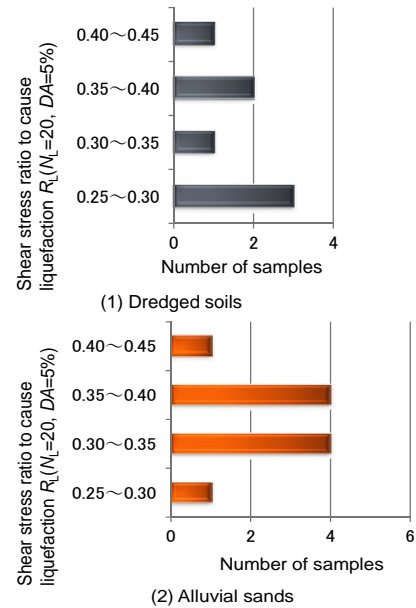


Figure 6 Frequency distributions of shear stress ratio to cause liquefaction

out detailed soil investigations in Summer by boring, SPT, CPT, PS logging, undisturbed sampling, cyclic triaxial tests and others, and reported valuable data in December 2011. Frequency distributions of normalized SPT N -values, N_1 and fines content, F_c of the F layer and the A_S layer are compared in Figures 5 (1) to (4). Fines content of the F layer are very scattered and greater than the fines content of the A_S layer, though the F layer was essentially taken from the A_S layer. This difference must be attributed to the lack of the alluvial sandy soils for the reclamation work. As the dredged zones were located just the top of a delta formed by Edo River, sandy soils were not enough for the filling, then some alluvial clays had to be excavated and mixed with the alluvial sandy soils. Average value of the fines content of the F layer is extremely high as 43.8 %. However, plasticity indexes, I_p are not high though their fines content are large. N_1 of the F layer is apparently lower than that of the A_S layer. Undisturbed samples were taken at nine sites to obtain cyclic shear strength and shear modulus. Frequency distributions of shear stress ratio to cause liquefaction in 20 cycles tested by cyclic triaxial tests, $R_L (N_L=20, DA=5\%)$ for the F and the A_S layers are shown in Figure 6. Dominant R_L values for the F layer and the A_S layer are 0.25 to 0.30 and 0.30 to 0.40, respectively though the data are very scatter in the F layer. Therefore it can be said the soils in the F layer are more liquefiable than those in the A_S layer.

PROCESS OF LIQUEFACTION

As the earthquake occurred at 14:46 in the afternoon on Friday, many important photos and movies were taken at many sites along Tokyo Bay to study the process and mechanism of liquefaction. Among them a series of photos taken by Mr. Katsunori Ogawa just after the earthquake at Maihama 3-chome in Urayasu City is introduced in Photos 1 (1) to 1 (4):

<<<Shake due to main shock started at 14:47 in Urayasu>>>

A <14:56>: Spew out of muddy water started in northeast direction. It took several minutes to start the boiling after the settle of the main shock.

B <15:01>: Boiled muddy water gradually spread and covered the road.

<<<A strong aftershock hit Urayasu at 15:16>>>

C <15:21>: The southwest road covered completely with muddy water. Water pipes look like to break.



Photo 1 Sequential photos taken by Mr. K. Ogawa

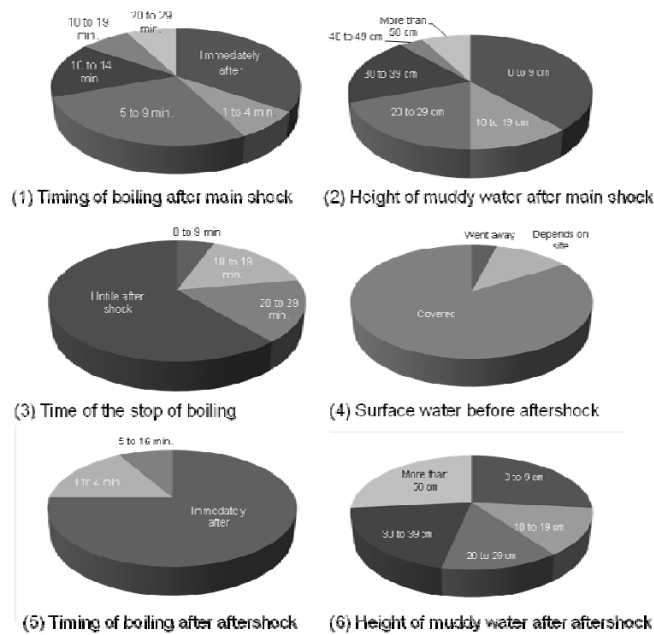


Figure 7 Questionnaires to inhabitants in Irifune

D <15:22>: Many houses settled and tilted and cars submerged in the boiled muddy water.

The authors sent out questionnaires to about 30 inhabitants in Irifune district which is also located in Urayasu City to ask the timing of boiling and height of boiled muddy water. Answers are summarized in Figure 7. 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. According to the hearing in Imagawa district some inhabitants testified boiling did not occur during main shock but occurred during aftershock.

EFFECT OF LONG DURATION OF SHAKING ON LIQUEFACTION

Figure 8 shows ground surface accelerations during the main shock and the aftershock. Surface accelerations were not high as around 160 cm/s² to 230 cm/s² though severe liquefaction occurred. The accelerograph recorded at K-NET Inage in Chiba where actually boiled sand was observed, is very important because liquefied time can be judged from the recorded waves. Figure 9 shows the accelerograph at Inage 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

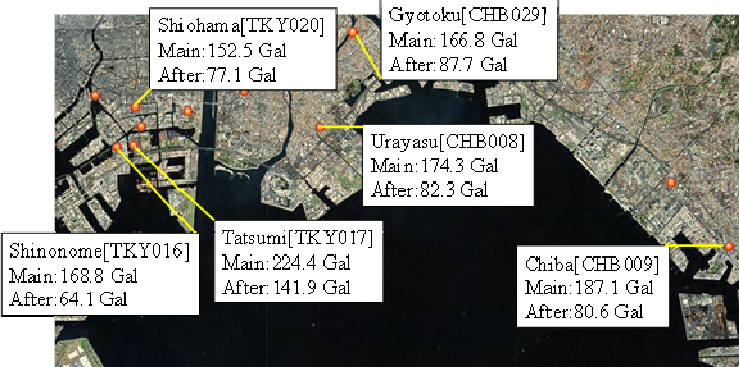


Figure 8 Comparison of accelerations during main and aftershocks by K-NET

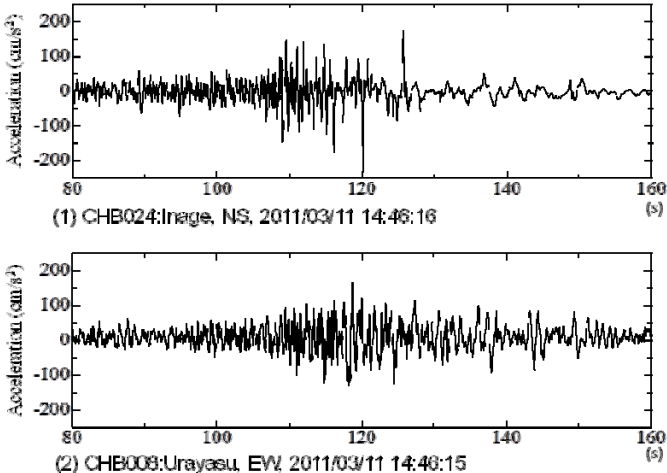


Figure 9 Comparison of accelerographs recorded at K-NET Inage and Urayasu

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. By referring to the accelerograph at K-NET Urayasu, shake of the ground at Inage continued for about 3 minutes after liquefied.

One more impact to the ground must be the shaking during the aftershock. Peak accelerations during the aftershock were almost a half of those during the main shock in Tokyo Bay area as shown in Figure 8. Even though, as mentioned above, boiling occurred after the aftershock at some site. Therefore, major reason of the severe liquefaction must be the effect of long duration of shaking during main shock and an aftershock. The authors tried to conduct cyclic torsional shear tests and some simple analyses to evaluate the effect of the long shaking on the occurrence of liquefaction. Two types of shear wave were applied to specimen, sine wave of 20 cycles and the seismic wave recorded during main shock and after shock at Urayasu K-NET. In case of seismic wave, excess pore water pressure increased gradually with shear stress as illustrate in Figure 10. Then, relationships between stress ratio R (τ_d / σ') for sine wave or R_{max} (τ_{max} / σ') for seismic wave and residual excess pore water pressure u/σ_c' are plotted in Figure

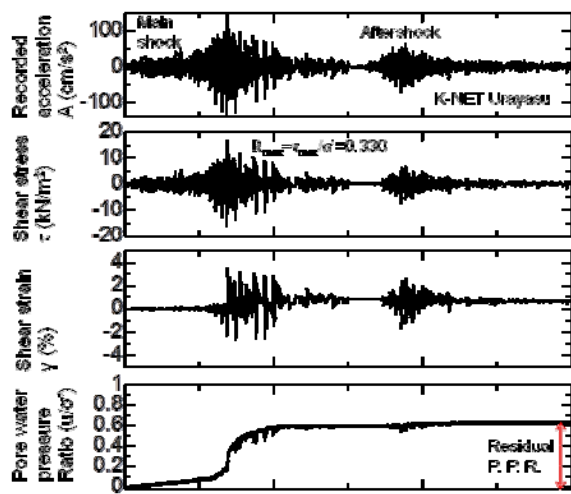


Figure 10 Time histories of shear stress, shear strain and excess pore water pressure

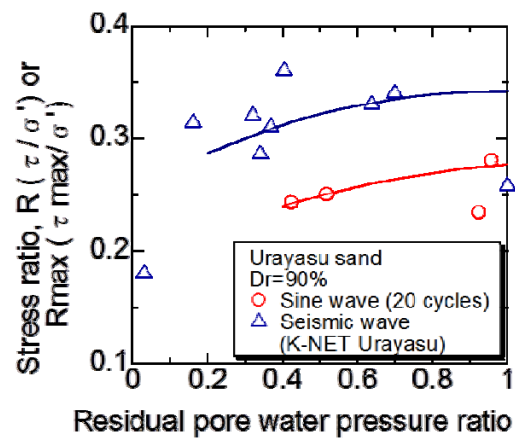


Figure 11 Relationship between shear stress ratio and excess pore water pressure

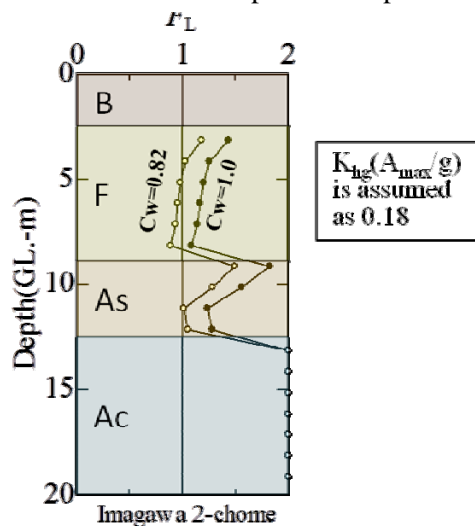


Figure 12 Analyzed F_L at Imagawa 2-chome Urayasu City

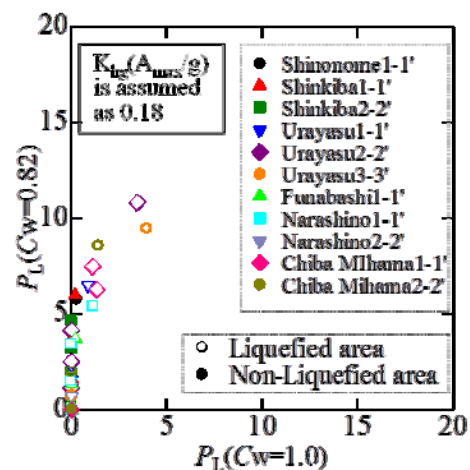


Figure 13 Effect of C_w on P_L

11. As $R=0.27$ for $u/\sigma'_c=1.0$ and $R_{max}=0.31$ for $u/\sigma'_c=1.0$, the correction factor C_w by JRA standard (2002) becomes 0.82. Then safety factor against liquefaction F_L and liquefaction potential P_L were evaluated for every boring data used for the estimation of 11 brief soil cross section, under the conditions of $C_w=0.82$ and 1.0. In the estimation, R_L was estimated from SPT N-values and F_c , by using the proposed formula by the technical committee of Urayasu City. Figure 12 shows evaluated F_L values for a boring data in Urayasu where liquefaction occurred. If the C_w is assumed as 1.0, all F_L are estimated greater than 1.0 whereas F_L are less than if C_w is assumed as 0.82. Figure 13 compares P_L for all boring data under the assumption of $C_w=0.82$ and $C_w=1.0$. If $C_w=0.82$, P_L for liquefied sites are calculated as greater than about 10 and severity of liquefaction can be demonstrated.

SETTLEMENT AND TILTING OF HOUSES

According to the result of totaling by the Ministry of Land, Infrastructure, Transport and Tourism, about 27,000 houses were damaged due to liquefaction as shown in Table 1. Photos 2 (1) and 1 (2) show a damaged house taken from outside and inside, respectively. The house settled and tilted about 40/1,000. In the heavily tilted houses, inhabitants feel giddy and nausea and difficult to live in their houses after the earthquake. However damaged houses due to liquefaction had been judged as partial collapse or injured only during past earthquakes because of no damage to walls and windows, though it has been desired both settlement and inclination must be considered in the judge.

Table 1 Number of damaged houses due to liquefaction (by the Ministry of Land, Infrastructure, Transport and Tourism)

Prefecture	Number of damaged houses
Iwate	3
Miyagi	140
Fukushima	1,043
Ibaraki	6,751
Gunma	1
Saitama	175
Chiba	18,674
Tokyo	56
Kanagawa	71
Total	26,914



(1) Outside of the tilted house



(2) Outside of the tilted house

Photo 2 Severely settled and tilted house in Urayasu City

Table 2 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 than floor
Large-scale partially destroyed	1/60 to 1/20	25 cm upper than footing to floor
Partially destroyed	1/100 to 1/60	Up to 25 cm upper than footing

Table 3 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	9,981

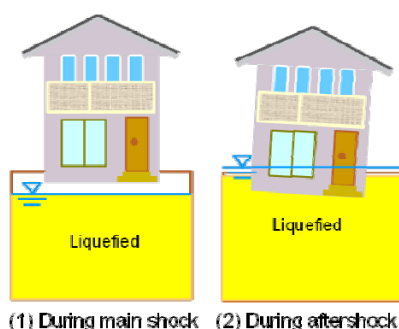


Figure 14 Possible effect of aftershock on the settlement of house

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 2. Numbers of damaged houses in Urayasu City by the new standard are listed in Table 3 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 3,680.

As mentioned above, occurrence of liquefaction must be affected by the aftershock. Not only the occurrence of liquefaction but also the settlement and inclination must be affected by the aftershock. Ground water table increased after the main shock and boiled muddy water covered the ground surface until the aftershock at many sites. 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 14.

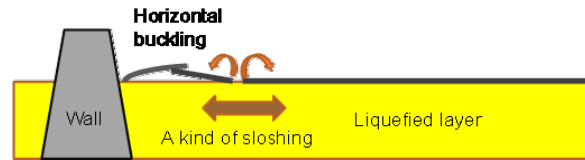
Many inhabitants along Tokyo Bay are facing to the serious problem how to restore the damaged houses. Complicated problem is the re-liquefaction during aftershocks or future earthquakes. Not only the restoration but also some countermeasure against re-liquefaction must be applied, but the problem is 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.

DAMAGE OF SEWAGE PIPES AND MANHOLES DUE TO SLOSHING OF LIQUEFIED GROUND

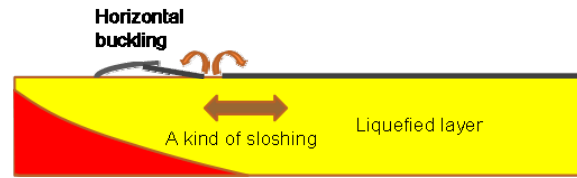
Miracle phenomena, heaving, buckling or thrust were observed at several footways and alleys as shown in Photo 3 at many sites in Tokyo Bay area. Some thrust might occur at the boundaries due to a kind of sloshing of liquefied ground as schematically shown in Figure 15 (1), because shaking continued for long time after the occurrence of liquefaction. Figure 16 shows heaved footways or alleys in Urayasu City together with contour lines of the thickness of the F layer under the ground water table. It may be said that the heaving occurred at the sites where the bottoms of the F layer, in other word liquefied layer,



Photo 3 Heaving of a footway at Takahama, Ichikawa City



(1) Horizontal buckling at a boundary



(2) Horizontal buckling on a sloped bottom of liquefied layer

Figure 15 Two possible mechanism of heaving

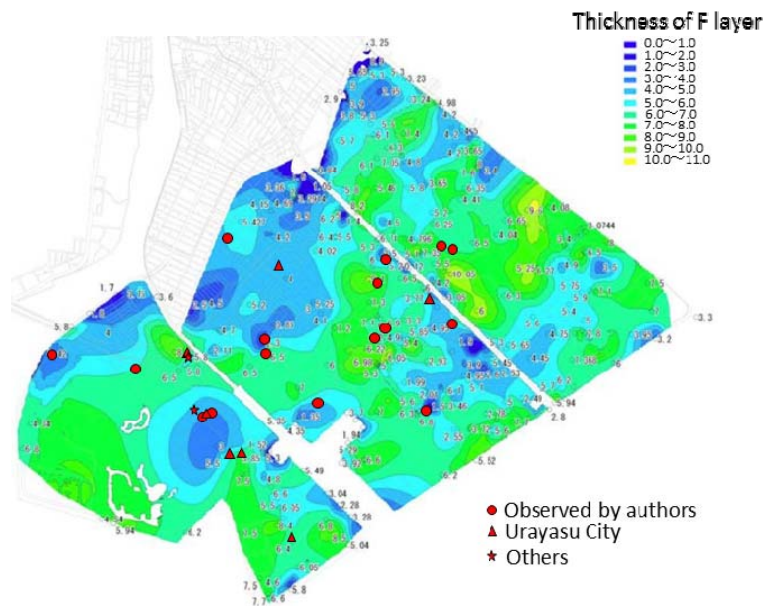


Figure 16 Heaved footways or alleys in Urayasu City together with contour lines of the thickness of the F layer under the ground water table (Contour lines are quoted from research materials (2011))

are sloped. This implies that a kind of horizontal buckling of surface layer might occurred due to the concentration of horizontal compressive stress as schematically shown in Figure 15 (2). However, more studies are necessary on the mechanism of the buckling.

In sewage facilities, pipes were meander or broken, joints were pulled out and pipes were filled with muddy water. Many manholes were sheared in horizontal direction and filled with muddy water whereas few manholes uplifted. Though the mechanism of these unique damages is still studying, one authors' idea is illustrated in Figure 17. As mentioned above a kind of sloshing of liquefied ground might occur due to long duration of shaking and caused thrust of roads. By the same movement of the ground, pipes might meandered violently in horizontal direction, resulting pull out or break of joints, and eventually liquefied muddy water invaded into the pipes. Manholes might be sheared due to horizontal force and pressurized liquefied muddy water came into the manholes. Fortunately or unfortunately invaded muddy water into the sewage pipes and manholes might prevent uplift.

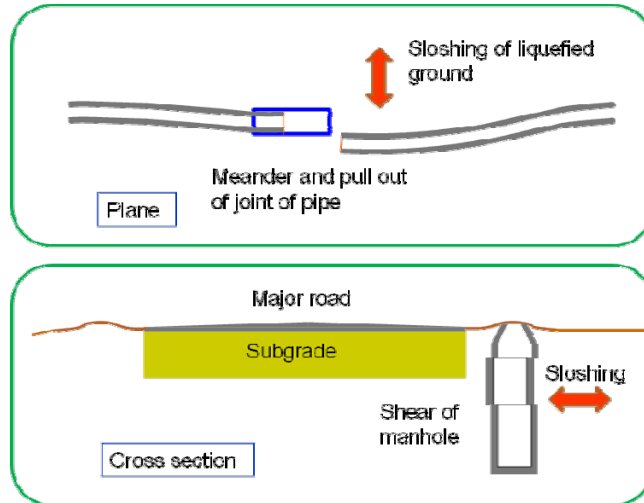


Figure 17 Unique damage to sewage manholes and pipes

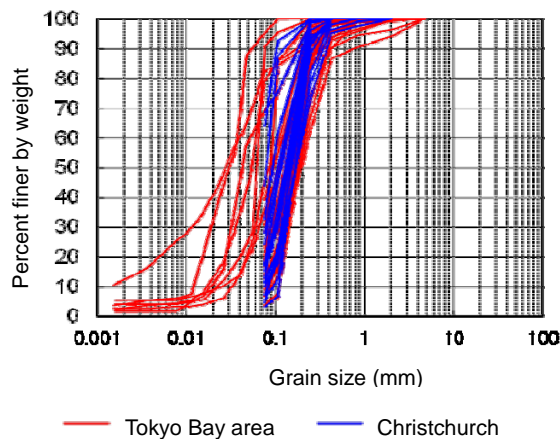


Figure 18 Comparison of grain size distribution curves of boiled sands in Tokyo and Christchurch



Photo 4 Thick boiled soil observed in Chiba City

TRAFFIC PROBLEMS DUE TO BOILED SAND AND SUBSIDENCE

Much eruption of sands and large ground subsidence occurred in the liquefied area. The maximum thickness of the erupted sand and the maximum ground subsidence observed by the authors were about 30 cm and 50 cm, respectively. This is the first experience for the authors to see such thick deposited boiled sand in Japan. However, one of the authors had seen similar much eruption and large subsidence in Christchurch during the main shock on September 2010 and aftershock on February 2011. Figure 18 compares grain size distribution curves of erupted soils in Christchurch during the main shock with those in Tokyo Bay during this earthquake. Fines contents for Christchurch and Tokyo Bay are similar. Then it is estimated that in the very fine sands, ejection of water continues for long time because of low permeability of liquefied soils in both area. Moreover fine soil particles are easy to uplift above the ground surface by the ejecting water. And the removal of the deposited soils by inhabitants accelerated the settlement of the ground surface.

Photo 4 shows an alley covered by boiled sands. It was difficult to run on the thick deposited wet sands by cars and bicycles. Moreover large settlement of the ground around buildings prevented to go out from parking spaces.

CONCLUSIONS

Severe liquefaction occurred by the 2011 Great East Japan Earthquake in Tokyo Bay area. Seismic intensities in the liquefied zones were not high, though the liquefied ground was covered by boiled sands. The very long duration of the main shock and an aftershock 29 minutes later should have induced the severe liquefaction. Many houses settled substantially and tilted seriously due to liquefaction. Sewage pipes meandered or were broken, joints were extruded from the ground, and pipes were filled with muddy water. Many manholes were sheared horizontally and filled with muddy water, whereas few manholes were uplifted. This remarkable damage to buried pipes and manholes might have occurred due to a kind of sloshing of liquefied ground.

ACKNOWLEDGEMENTS

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