Remarkable liquefaction-induced damages along Tokyo Bay during during the 2011 Tohoku-Pacific Ocean earthquake in Japan.

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SUMMARY
The 2011 Tohoku-Pacific Ocean earthquake caused severe liquefaction in the reclaimed lands in the Tokyo Bay area. The liquefied area was very wide as about 41 km^2 though epicentral distance was about 380km. 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. Sewage pipes meandered or were broken, their joints were extruded from the ground, and many manholes were sheared horizontally. These remarkable damage might have occurred due to a kind of sloshing of liquefied ground.

Keywords: liquefaction, reclaimed land, very long shaking, sewage facilities, road

1. INTRODUCTION

The 2011 Tohoku-Pacific Ocean 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, 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 Chibaken-toho-oki Earthquake. However, the Tohoku-Pacific Ocean 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.

2. HISTORY AND PROCESS OF RECLAMATION IN TOKYO BAY AREA

Tokyo Bay is an egg-plant shaped big bay facing to Pacific Ocean with a length of about 60 km and a width of about 20 km. Many middle-scale rivers, Tama, Sumida, Arakawa, Edo and other rivers flow into the bay by transporting soils from surrounding mountains 1000 to 2000 m high, result to form deltas along Tokyo Bay. In 1603 Japanese capital, governed by Shogun moved from Kyoto to the area facing to Tokyo Bay and the new capital was named as Edo which was renamed to Tokyo after the revolution by citizen in 1968. The reclamation of coastal areas of Tokyo Bay started after the movement of capital to Edo in 17th Century and accelerated after the revolution in 19th Century because of the increase of population. As illustrated in Figure 1 (Endo, 2004), the first reclamation area was the estuaries of Sumida and Arakawa rivers in Tokyo and extended to Yokohama which is the major port in Tokyo Bay Area. After the Second World War very wide area along Tokyo Bay was reclaimed from Kanagawa Prefecture to Chiba Prefecture through Tokyo for industrial and residential purposes.

As demonstrate later, 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 as shown in Figure 1. Therefore it may be said that young

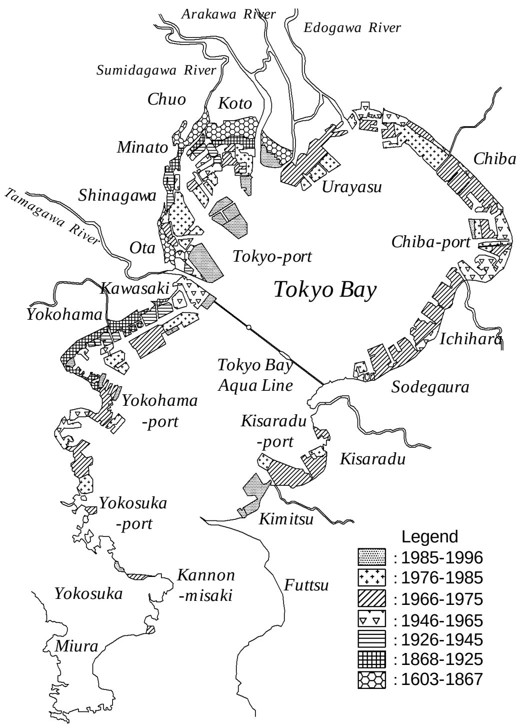


Figure 1. History of reclamation in Tokyo Bay area (Endo, 2004)

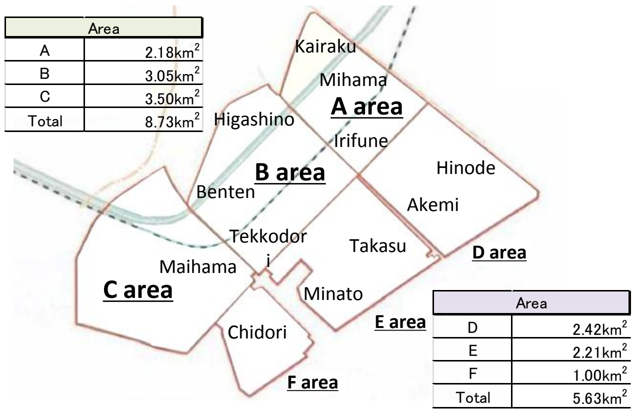


Figure 2. Detail history of reclamation in Urayasu (Urayasu City)

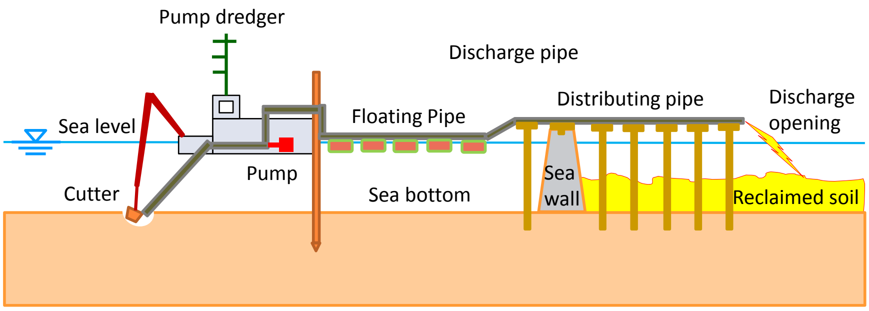


Figure 3. Process of dredging work

reclaimed soils liquefied by the earthquake. However, this conclusion is too hasty because seismic intensity in this area was stronger than that in other area in Tokyo Bay area. Detailed history of reclamation work in Urayasu City where serious damage to numerous houses occurred, is explained in Figure 2. Urayasu City is classified into three towns, Motomachi, Nakamachi and Shinmachi which mean old, middle and new towns, respectively. The ground of Old Town has been formed naturally at the estuary of Edo River. On the contrary the zones A, B and C which locate in Nakamachi were firstly reclaimed from 1965 and continually the zones D, E and F which locate in Shinmachi were reclaimed from 1972. Area of each zone is 1.0 to 3.5 km^2, and total area of Nakamachi and Shinmachi is 14.36 km^2 which is about 3/4 of the whole area of Urayasu City. 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 transported by boats from Boso Peninsula. Figure 3 draws the process of the dredging work. The soils of sea bottom just outside of the zones of C, F and D were excavated by a cutter, exhausted with water by a pump, transported by a convey pipe then discharged from the exit of 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 such as Disney Land and several housing lots where sand compaction piles or gravel drain piles and other methods were applied to prevent liquefaction.

3. 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 Figure 4. The zones surround by red lines were judged to be liquefied, but. note is necessary that some small districts in the zones did not liquefy because their grounds had been improved by sand compaction method or other methods. 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 5 is the map of liquefied zones thus estimated which is slightly modified from the tentative map.

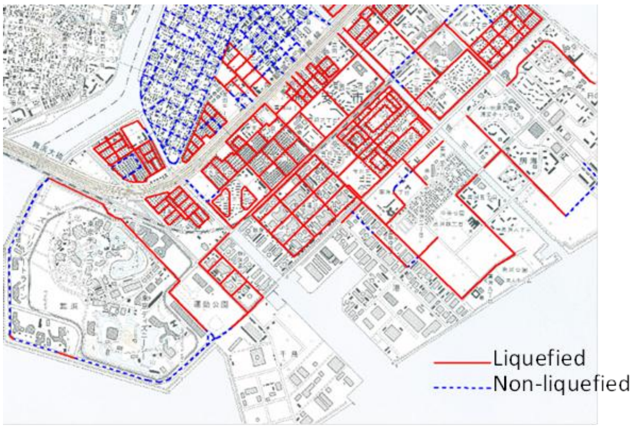


Figure 4. Method to judge liquefied and non-liquefied zones

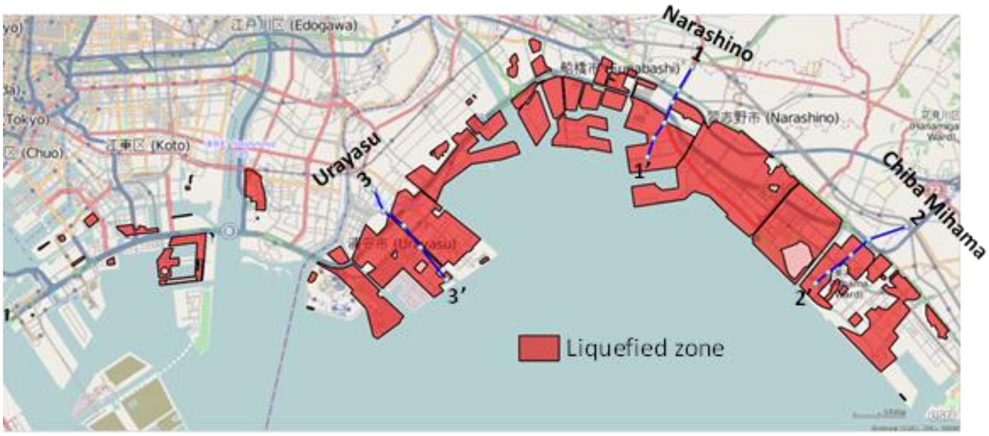


Figure 5. Liquefied area from Odaiba in Tokyo to Chiba City (Joint research by Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism and JGS)

4. ESTIMATION OF BRIEF SOIL CROSS SECTIONS IN THE LIQUEFIED AREA OF TOKYO TO CHIBA

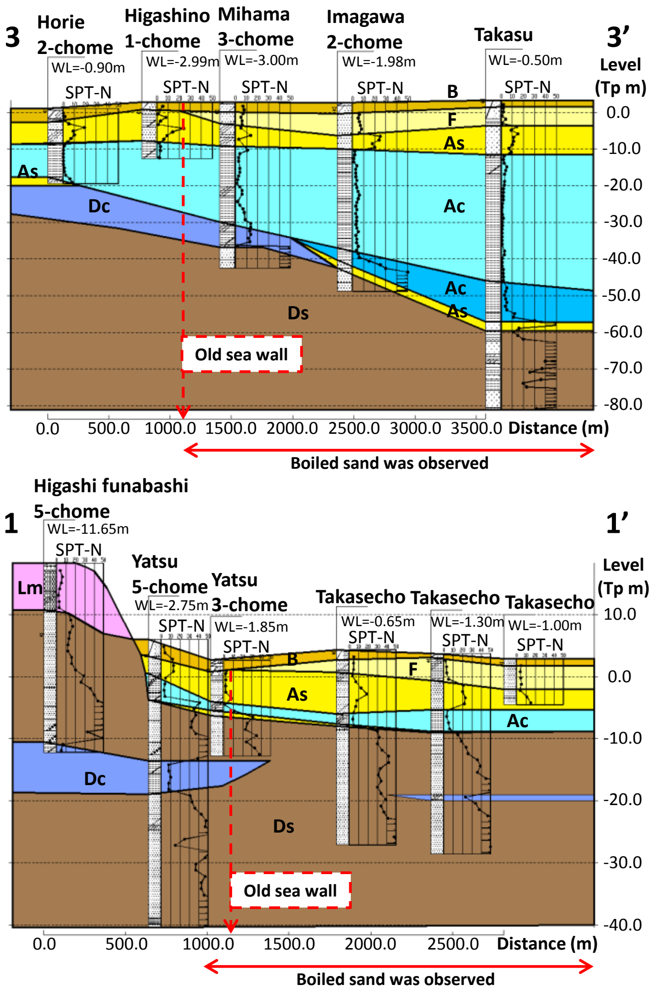
In Japan, recently, geotechnical data bases have been prepared and published on internet at many cities and prefectures. JGS also published geotechnical data bases in several districts (Yasuda et al., 2010). As three sets of data base had been published by JGS, Chiba Prefecture and Tokyo Metropolitan 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. Figures 6 (1) to (3) illustrate the estimated soil cross sections along three lines together with the zones where sand boils were observed.

The soil cross section shown in Figure 6 (1) is the section along the line Urayasu 3-3’ where many houses and lifelines suffered very serious damage due to liquefaction. 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 (As) 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 As 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, As layer deposited from ground surface. Therefore it can be estimated that the As layer basically did not liquefy by the 2011 Tohoku-Pacific Ocean 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. In the cross section shown in Figure 6 (2), Ac layer is thin because this site is not a delta but a seashore with a behind-standing terrace in topographical condition. In the cross section of Mihama 1-1’, As layer is thicker than other sections. However, thickness and SPT N-values of B and F layers and the depth of water table in reclaimed lands are similar in all section.

Urayasu
3-3’ Line

Narashino
1-1’ Line



Figures 6 (1) to (2). Estimated brief soil sections

Chiba Mihama
2-2' Line

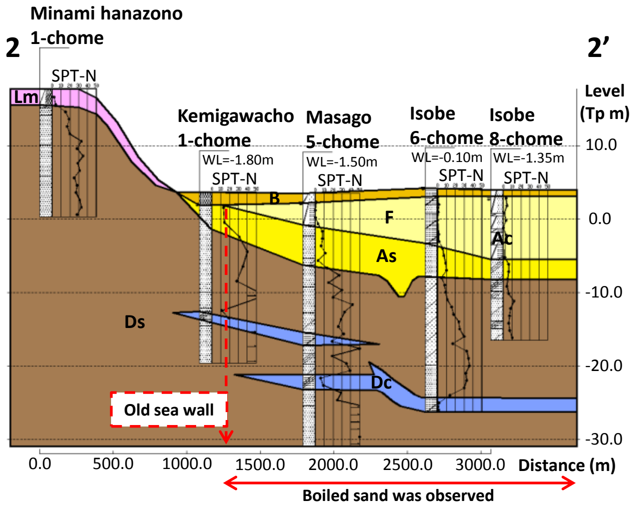


Figure 6 (3). Estimated brief soil section

5. EFFECT OF LONG DURATION OF SHAKING ON LIQUEFACTION

Figure 7 shows ground surface accelerations during the main shock and the aftershock. Surface accelerations were not high as around 160 cm/s^2 to 230 cm/s^2 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 8 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 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 7. Even though, 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 9. 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 10. As R=0.27 for u/σ_c'=1.0 and R_{max}=0.31 for u/σ_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 11 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 12 compares P_L for all boring data under the assumption of C_w=0.82 and C_w=1.0. If Cw=0.82, P_L for liquefied sites are calculated as greater than about 10 and severity of liquefaction can be demonstrated.

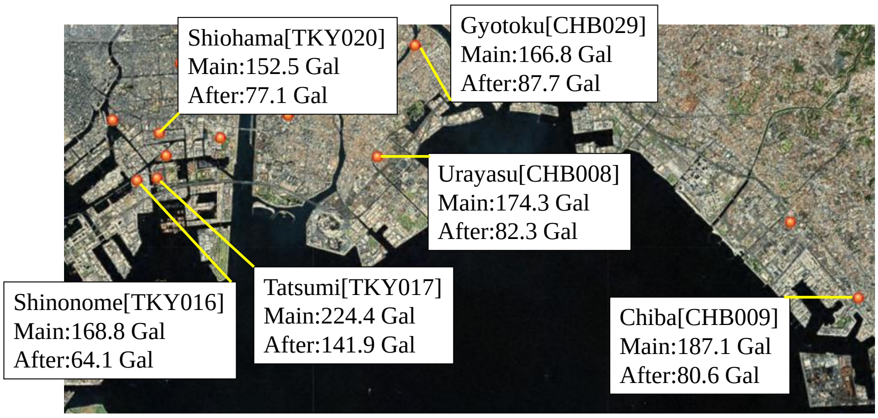


Figure 7. Comparison of accelerations during main and aftershocks by K-NET

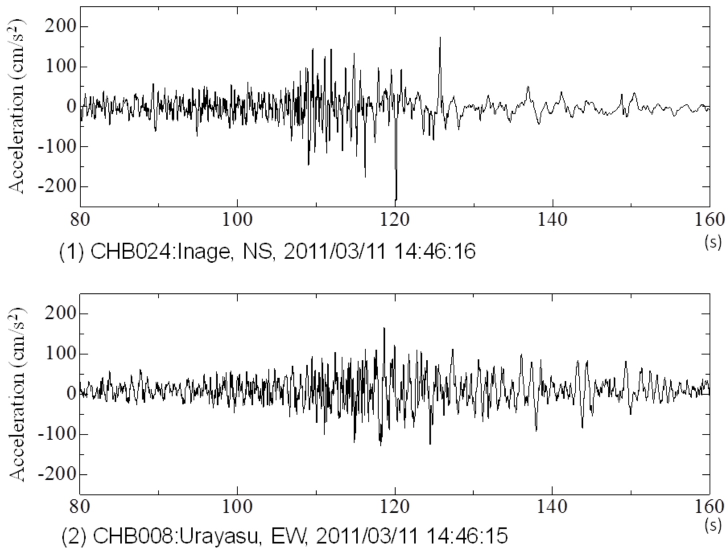


Figure 8. Comparison of accelerographs recorded at K-NET Inage and Urayasu

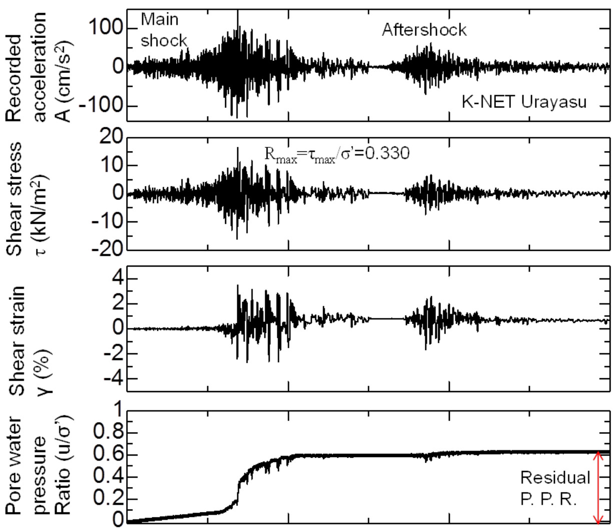


Figure 9. Time histories of shear stress, shear strain and excess pore water pressure

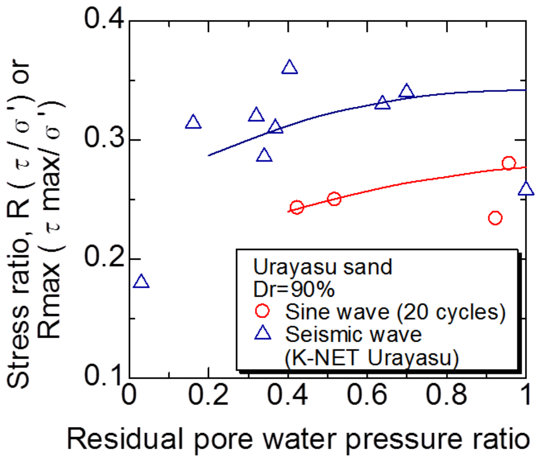


Figure 10. Relationship between shear stress ratio and excess pore water pressure

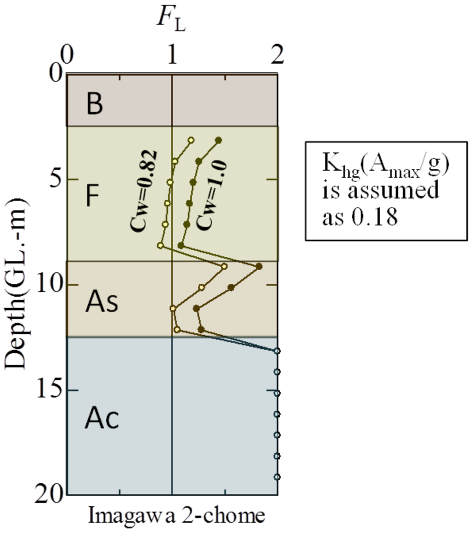


Figure 11. Analyzed F_L at Imagawa in Urayasu City

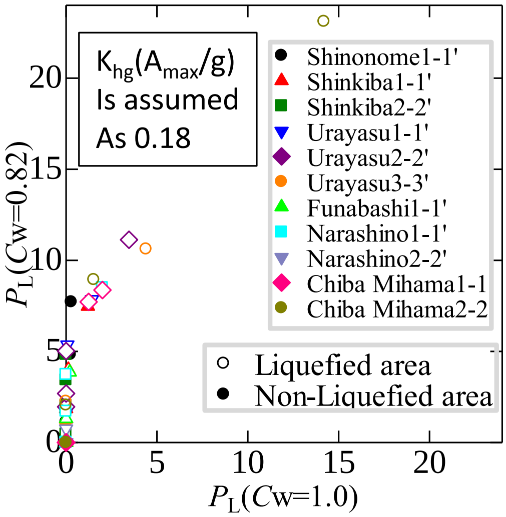


Figure 12. Effect of C_w on P_L

6. 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 1 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 13 (1), because shaking continued for long time after the occurrence of liquefaction. Figure 14 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, 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 13 (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 15. 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.

Photo 1. Heaving of a footway at Takahama, Ichikawa City

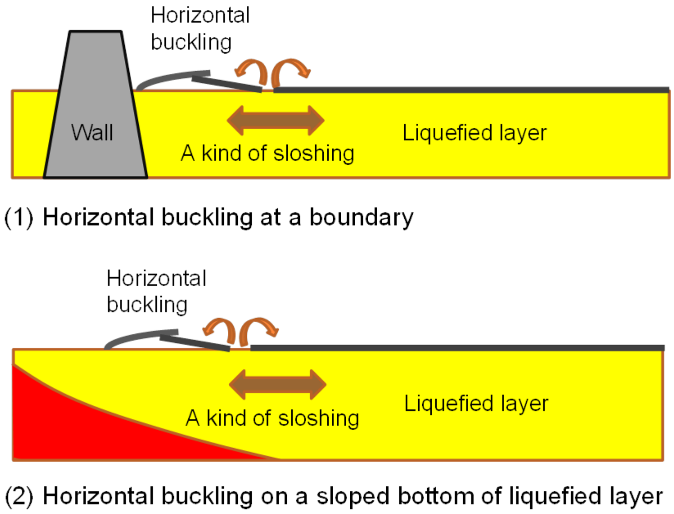


Figure 13. Two possible mechanism of heaving

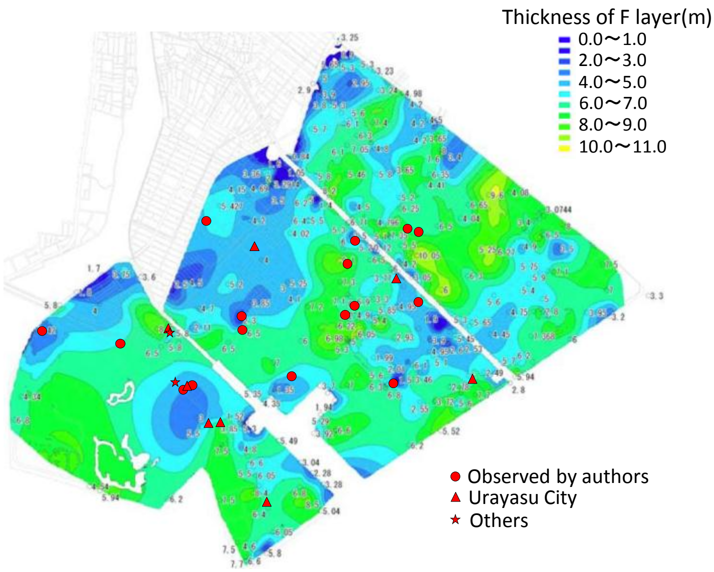


Figure 14. Heaved footways or alleys in Urayasu City together with contour lines of the thickness of the F layer under the ground water table (Contour lines are quotedfrom research materials (2011))

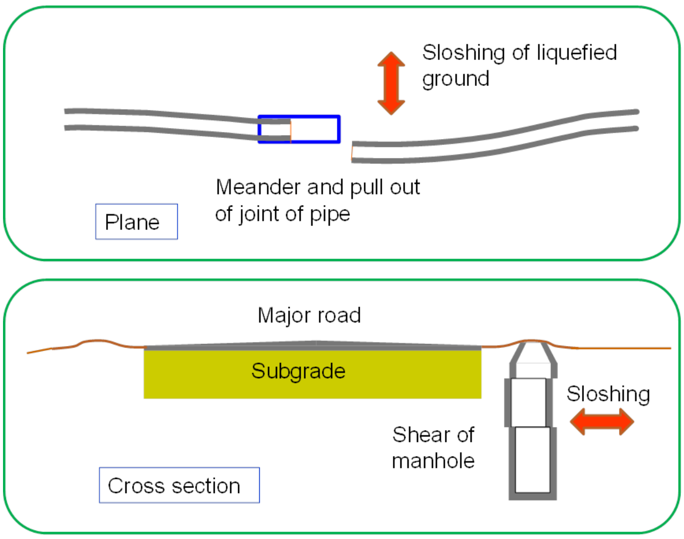


Figure 15. Unique damage to sewage manholes and pipes

7. CONCLUSIONS

The 2011 Tohoku-Pacific Ocean earthquake caused severe liquefaction in the Tokyo Bay area. The authors conducted or reviewed several studies on the soil conditions and the damage to structures of the liquefied sites. The following conclusions were derived from these studies:

(1) Severe liquefaction occurred in reclaimed lands from Shinkiba in Tokyo through Urayasu, Ichikawa and Narashino cities to Chiba City. These lands were constructed after around 1966 by soils dredged from the bottom of the bay.

(2) 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.

(3) Lifelines and roads were severely damaged in the liquefied zones. The minor roads and sidewalks suffered severe damage, such as settlement, waving, heaving and cracks. 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.

ACKNOWLEDGEMENT

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