Effect of post-liquefaction long shaking on roads and buried pipes during the 2011 Great East Japan Earthquake

I. Suetomi [(1)], H. Shinkai [(2)], W. Inomata [(3)], R. Hamanaka [(4)], S. Yasuda [(5)], N. Ohbo [(6)]

[(1)] *Eight-Japan Engineering Consultants Inc., suetomi-i@ej-hds.co.jp*
[(2)] *Tokyo Gas Co.,Ltd., hshinkai@tokyo-gas.co.jp*
[(3)] *Tokyo Gas Co.,Ltd., inomataw@tokyo-gas.co.jp*
[(4)] *Tokyo Gas Co.,Ltd., ryo-hamanaka@tokyo-gas.co.jp*
[(5)] *Professor, Tokyo Denki University, yasuda@g.dendai.ac.jp*
[(6)] *Association for the Development of Earthquake Prediction, ohbo@8f.adep.or.jp*

Abstract

The 2011 Great East Japan Earthquake, a megathrust earthquake with a magnitude of Mw=9.0, occurred in the Pacific Ocean. The rupture plane of this quake was about 450 km in length and 200 km in width. The duration of the failure of the rupture plane was extremely long, about 160 seconds.

Soil liquefaction occurred in wide area including Tokyo Bay area. Many houses, river dikes and other structures severely settled or uplifted by liquefaction. Not only the settlement and uplift of the structures but also remarkable damage of buckling of roads, disconnection of buried pipes and the shear failure of sewage manholes occurred. This was the first experience that these remarkable damages were observed in the liquefied ground though many past earthquakes caused liquefaction frequently in Japan.

As many seismic records were obtained in the Tokyo Bay area, the authors collected many accelerograms at liquefied and not liquefied sites and estimated time histories of velocity, displacement and non-stationary spectra. Among them, accelerograms recorded at K-NET Inage in Chiba where boiled sand was observed are very important because the liquefaction time can be judged from the recorded waves. In Inage's wave, the amplitude of acceleration decreased suddenly at around 126 sec., which means liquefaction occurred at this moment. Then large amplitudes of velocity and displacement continued after 126 sec. for more than two minutes with a predominant period of 3 to 4 seconds. Such amplitudes of velocity and displacement were not induced at not liquefied sites. The long-period shaking of liquefied ground, which was a kind of sloshing, was recorded by several inhabitants on video. Slow cyclic horizontal movement at an amplitude of about 15 cm was seen in a video taken two minutes after the peak acceleration in Urayasu City. During the investigation of damaged area, strange thrusts and heavings of footways and alleys were seen at many sites. So, it seemed that some boundaries beside the footways and alleys, such as banks of old sea walls and elevated bridges, caused the thrusts or heavings due to the sloshing of liquefied ground. A lot of sewage, water and gas pipes were deformed, cracked, broken and meandered, and joints were sheared or disconnected. Many sewage manholes were cracked and sheared in the horizontal direction. So, it was concluded that the large horizontal displacement of liquefied ground had to have caused large cyclic compressional and tensile stress to the pipes in horizontal direction, resulting in the disconnection of the pipe joints and the shear failure of the manholes.

Keywords: megathrust earthquake, liquefaction, sloshing

1. Introduction

The 2011 Great East Japan Earthquake, a megathrust 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. Soil liquefaction occurred in the Tohoku region of northeastern Japan and in the Kanto region surrounding Tokyo because the earthquake was huge. The distance between the northernmost and the southernmost liquefied sites was about 600 km. Many houses, roads, lifeline facilities, and river dikes were severely damaged by liquefaction, and some port and harbor facilities, tank yards, electric power stations and tailing dams were also damaged in both the Tohoku and the Kanto regions. In the Tokyo Bay area, the southern district of the liquefied area, though the epicentral distance was very large, about 380 to 400 km, severe liquefaction occurred in a wide area because many liquefiable reclaimed lands had been constructed along Tokyo Bay. As the 2011 Great East Japan Earthquake was huge in scale, the duration of the main shock was very long, and it was followed by many big aftershocks.

The estimated liquefaction area by the real-time disaster prevention system "SUPREME" by Tokyo Gas supply system correspond actual liquefaction area very well [1], but remarkable, serious liquefaction-induced damage was caused. Many houses settled and tilted due to the main shock and to a big aftershock 29 minutes later, and a kind of sloshing of liquefied grounds occurred and caused the buckling of roads and the shear failure of sewage manholes. In this paper, the effect of the very long duration of the main shock and of the aftershock on the occurrence of liquefaction and associated damage to houses, roads and sewage facilities are discussed.

2. Liquefied Sites in Tokyo Bay Area and Damages of Buried Pipes

As the liquefaction-induced damage to houses, river dikes, roads, and lifeline facilities was serious, the Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism conducted joint research with JGS to identify liquefied sites. The results of their joint research were published on the government ministry's website [2]. Figure 1 shows a map of the liquefied sites in the Tokyo Bay area.

All of the northern part of Tokyo Bay liquefied, but in the eastern and western parts of Tokyo Bay, liquefaction was observed only in spots (Yasuda et al. [3, 4]). In the northern part of Tokyo Bay, the ground surface was covered with boiled sands all around the reclaimed lands in Shinkiba in Tokyo, Urayasu City, Ichikawa City, Narashino City and western Chiba City. In contrast, boiled sands were observed only here and there in the reclaimed lands in Odaiba, Shinonome, Tatsumi, Toyosu and Seishin in Tokyo and in eastern Chiba City. The total liquefied area from Odaiba to Chiba City reached about 42 km^2. Many houses, roads, and lifeline facilities were severely damaged in the liquefied zones. The most serious damage was in Urayasu City, where about 85% of the city foundation soil liquefied. The epicentral distance of the liquefied area in Tokyo Bay was very long, around 400 km. However, the distance from the boundary of the rupture plane was only 110 km because the rupture plane was very wide. Hatanaka et al. [5] reported in detail on the damage by liquefaction in Narashino city.

One of the authors visited Takasu and Imagawa in Urayasu on the day after the earthquake and was surprised that a footway heaved and an alley thrust, as shown in Figures 2. On the other hand, at Maihama in Urayasu, the thrust of an alley was observed though there was no such boundary, as shown in Figure 3.

In the case of Figure 2, the first impression was that the footway heaved due to uplift force of some buried pipes, such as sewage pipes. However, after that, strange thrusts and heavings of footways and alleys were also found in Ichikawa, Chiba and other cities. So, he concluded that some boundaries beside the footways and alleys, such as banks of old sea walls and elevated bridges, caused the thrust or heaving due to a kind of sloshing of liquefied ground, as schematically shown in Figure 4 (1), because shaking continued for a long time after the occurrence of liquefaction, as mentioned above.

In the case of Figure 3, the locations of heaved footways and alleys in Urayasu City, with and without boundaries, are plotted in Figure 5. By comparing the locations of heaved footways and alleys without boundaries with the contour lines of the thickness of the filled layer under the groundwater table, it may be said that the heaving occurred at the sites where the bottoms of the fill layer, in other words, the liquefied layer, was sloped. This implies that a kind of horizontal buckling of the surface layer might have occurred due to the concentration of horizontal compressive stress, as schematically shown in Figure 4 (2).

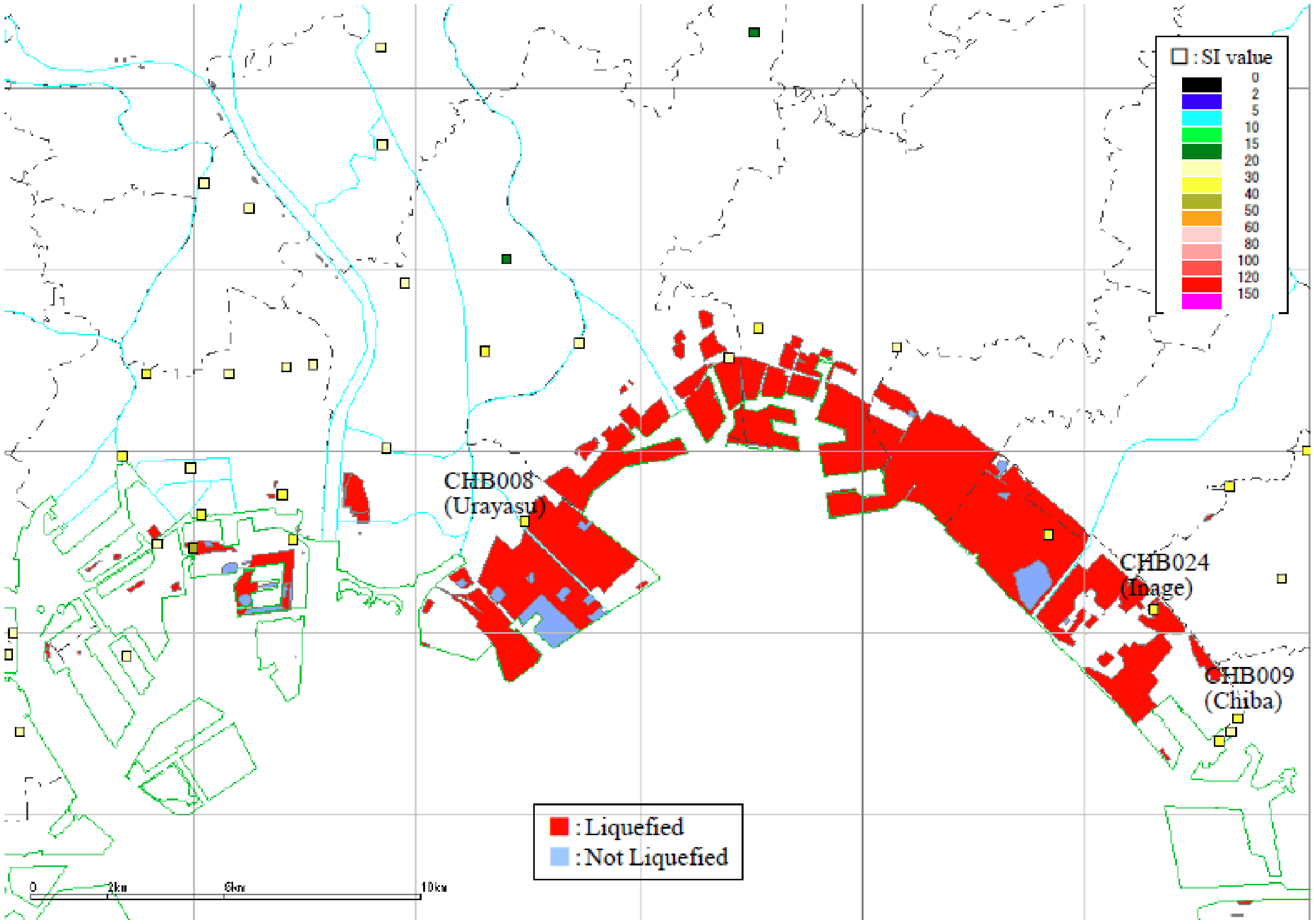


Fig. 1 Areas of Liquefaction in the Tokyo bay Area (Investigated by MLIT and JGS) and Observed SI values.

Fig. 2 Heaving of a footway in the Takasu district of Urayasu City

Fig. 3 Thrust of an alley in the Maihama district of Urayasu City (Photo by Ogawa)

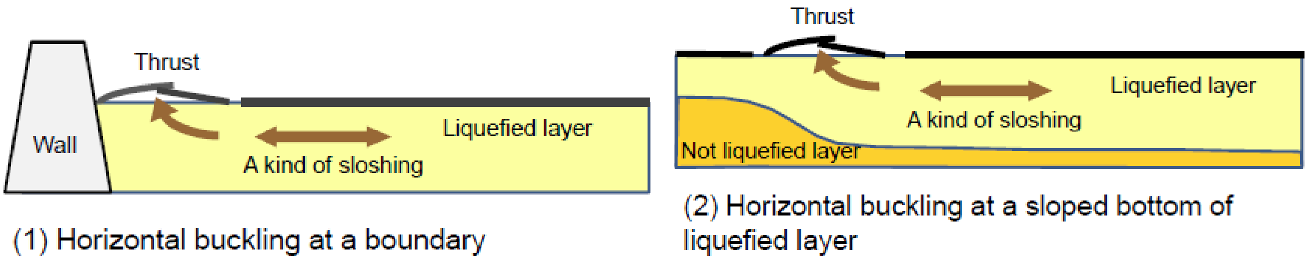


Fig. 4 Two possible mechnisms of thrust heaving of the ground

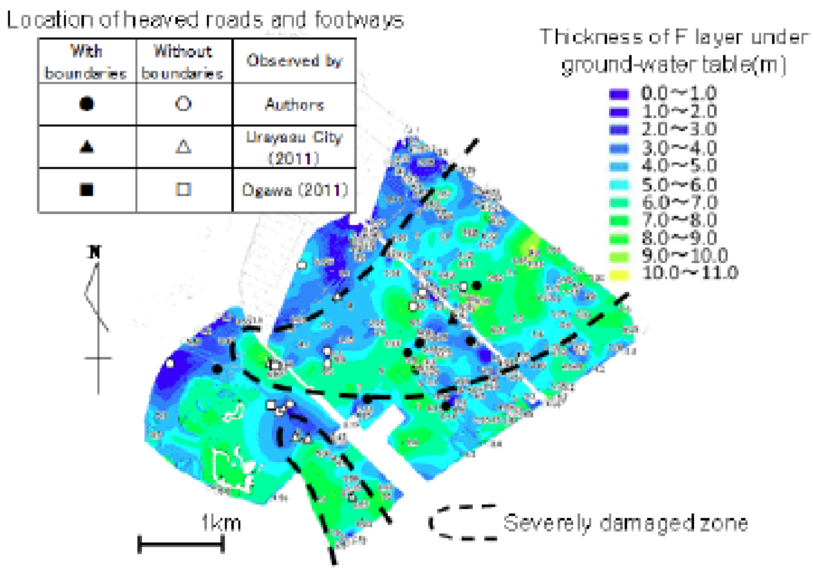


Fig. 5 Estimated thickness of F layer under groundwater table (by Urayasu City, 2012 [6]) and locations of thrusted roads and footways (Yasuda et al., 2012 [3])

Lifeline facilities for water, sewage, gas, electric power and telephones were severely damaged in the liquefied area. According to the MLIT, sewage pipes and manholes were damaged in 132 cities, towns and villages. Of 65,001 km of sewage pipes in the cities, towns and villages, 642 km were damaged. As shown in Figure 6, 65.9% of the damage to pipes was due to the liquefaction of filled soils and 24.5% was due to the liquefaction of both filled soils and the surrounding ground. Of the damage to manholes, 41.7% was due to the liquefaction of filled soils and 26.7% was due to the liquefaction of filled soils and the surrounding ground. The damage due to the liquefaction of both filled soils and surrounding ground mainly occurred along Tokyo Bay.

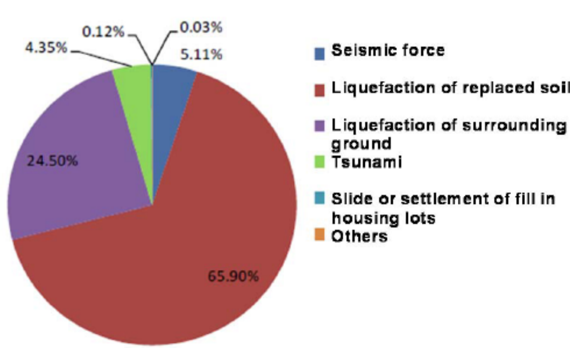


Fig. 6 Triggers to the damage of sewage pipes (Partially quoted from MLIT)

In the Tokyo Bay area, sewage pipes were deformed, cracked, broken and meandered, and joints were sheared or disconnected, as schematically shown in Figure 7. Muddy water seeped into the damaged pipes and closed pipes completely. Many sewage manholes were cracked and sheared in a horizontal direction and filled with muddy water, as shown in Figure 8, while a few manholes were lifted or slightly settled. Shear damage to manholes had not occurred during past earthquakes in Japan. During the construction of the manholes and pipes, the ground was excavated to a width of about 2m. After placing the manholes and pipes, the excavated area was filled with sand. During past earthquakes, only the fill soils were liquefied and sewage pipes and manholes uplifted, as schematically shown in Figure 8. But during the 2011 Great East Japan Earthquake, both the fill soils and the surrounding soils were liquefied and a kind of sloshing of liquefied ground might have occurred due to the long duration of shaking and caused the thrust of roads in the Tokyo Bay area. The large horizontal displacement of liquefied ground had to have caused the disconnection of the pipe joints and the shear failure of the manholes, allowing the influx of muddy water into the pipes and manholes. Fortunately or unfortunately, this muddy water might have prevented uplift.

In the following section, the feature of earthquake ground motion in the Tokyo Bay area is examined based on the observed ground motion records.

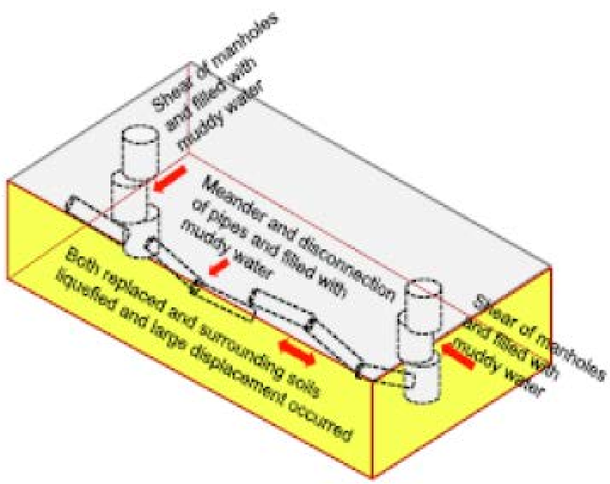


Fig. 7 Damage to sewage pipes and manholes due to the liquafaction of replaced soils and surrounding grounds

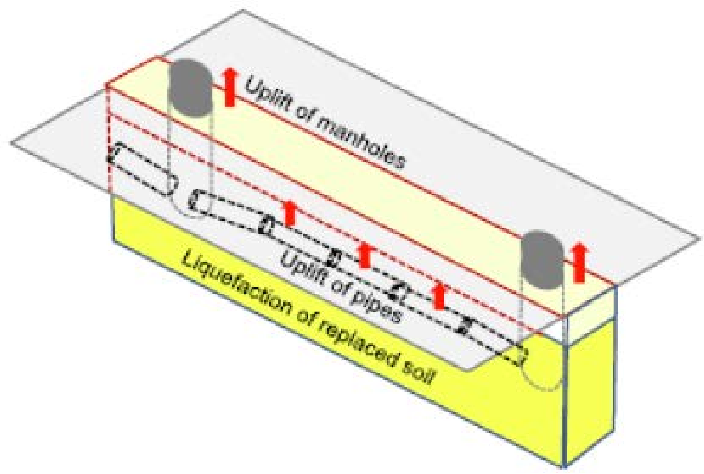


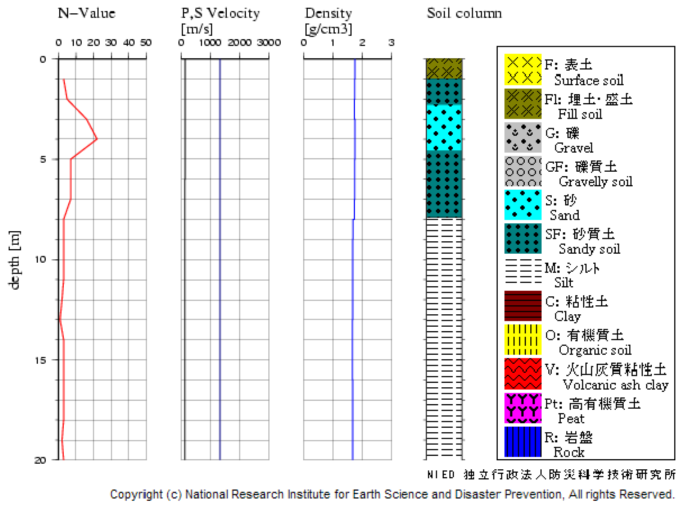
Fig. 8 Damage to sewage pipes and manholes due to the liquefaction of replaced soils

3. Effect of Seismic Ground Motions with Long Duration and Long Period

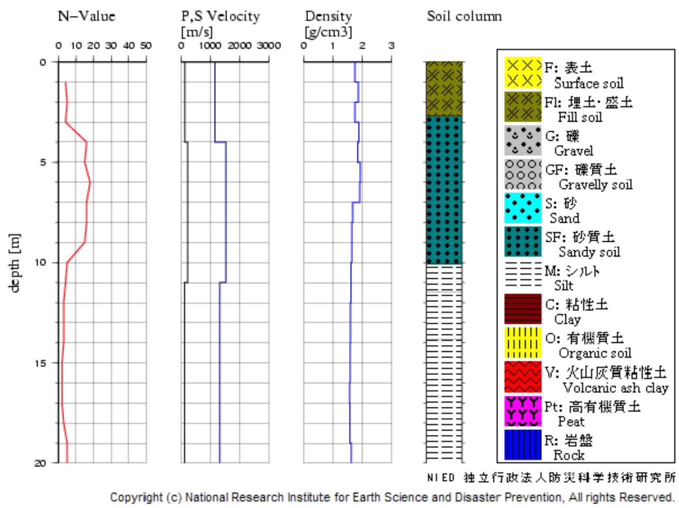
In the Tokyo Bay area, though surface accelerations were not high, about 160 cm/s^2 to 300 cm/s^2, due to the huge scale of the earthquake, the duration of shaking was extremely long and accompanied with strong aftershocks in a short interval.

Among many seismic records obtained in the Tokyo Bay area, the observed records at three K-NET sites plotted in the Figure 1 are examined, where borehole data are published on the web site [7]. Soil profiles from borehole data are shown in Figure 9.

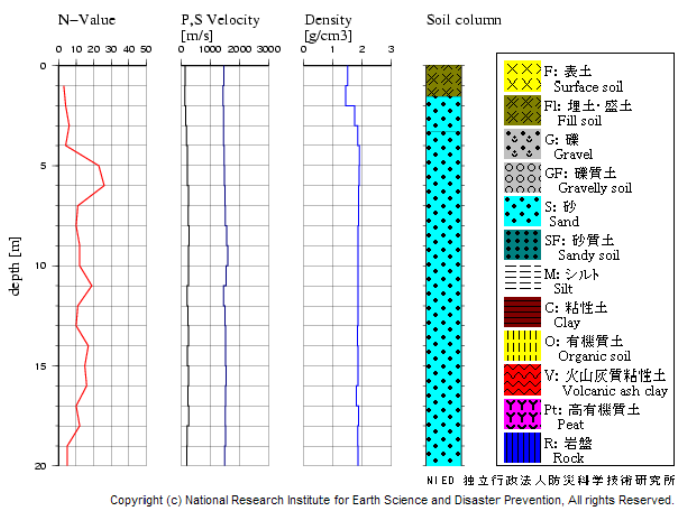
The surface layer at CHB008 is sandy soil but was not liquefied, since N-values are larger than those at reclaimed lands. Soils deeper than 8m are clay. Similarly, the surface layer at CHB009 was not liquefied, since soils deeper than 10m are soft silt. On the other hand, N-values of shallow sandy layers at CHB024 are smaller than 10. Consequently, many boiled sands were observed, so it is clear that the liquefaction occurred in the site.



(a)CHB008(Urayasu)



(b)CHB009(Chiba)



(c)CHB024(Inage)

Fig. 9 Soil profiles at K-NET observation site

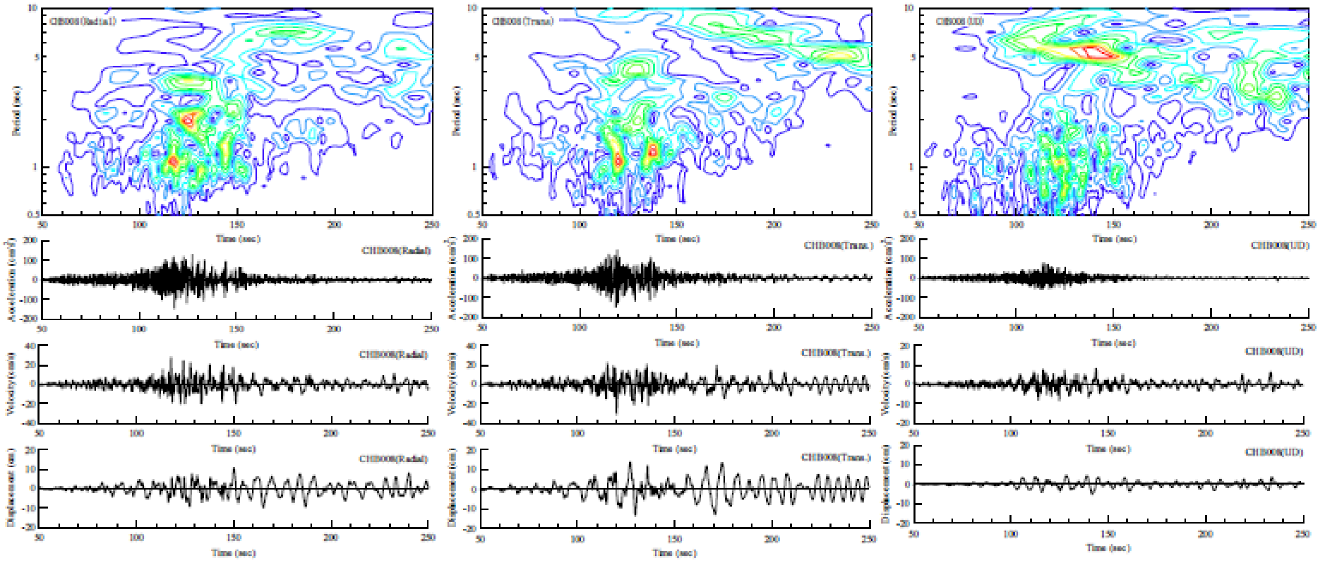
Non-stationary spectra [8] of velocity waves observed at three K-NET sites are shown at Figures 10 to 13. Radial and transverse components are calculated by the condition that waves are propagated from the direction of 50 degrees from the north.

In the transverse component, waves of 4 sec period are predominant in the back part of the principal motion. Waves of around 8 sec reach later than the principal motion and show the dispersion characteristics, so they are seems to be typical Love waves. Though it is similar in the radial component, waves of 5 sec period are predominant in the vertical component, which seems to be Rayleigh waves.

Among them, accelerograms recorded at K-NET Inage in Chiba, shown in Figure 12, where boiled sand was observed are very important because the liquefaction time can be judged from the recorded waves. Figure 10 shows the accelerograph recorded at Urayasu on ground where liquefaction did not occur. Both records started at almost the same time; 14:46:16 at Inage and 14:46:15 at Urayasu. At Urayasu, the wave frequency did not change drastically after the peak acceleration, which was induced at about 118 sec. (14:48:13). On the contrary, at Inage, the wave frequency dropped to a low value after two peaks at 120 sec. (14:48:16) and 126 sec. (14:48:22) and the amplitude of acceleration decreased suddenly. Therefore, it can be judged that liquefaction occurred at around 14:48:16 to 14:48:22 at Inage. This means many cycles of shear stress, say around 20 cycles over 110 sec., might have caused liquefaction at the Inage site.

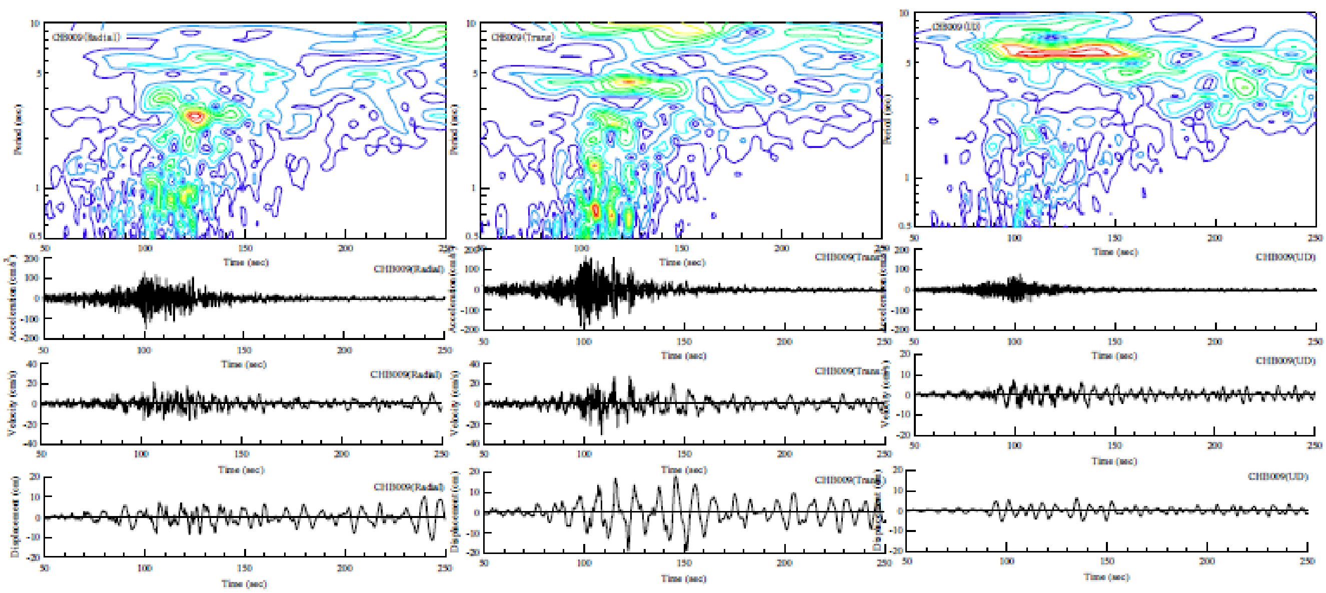
Time histories of velocity, displacement and non-stationary spectra estimated from the recorded acceleration are shown. In Inage's wave, though the amplitude of acceleration decreased suddenly at around 126 sec., large amplitudes of velocity and displacement continued after 126 sec. for more than two minutes with a predominant period of 3 to 4 seconds. Such amplitudes of velocity and displacement were not induced in Urayasu's wave. Shaking continued at a long predominant period for a long time after the occurrence of liquefaction.

In the rather long-period range from 1 to 5 seconds, non-linear effect of surface soil should be considered. So, the spectral ratios of horizontal to vertical (H/V spectra) are calculated in the 4 sections as shown in Figure 14. Predominant periods are almost constant at CHB008 and CHB009. On the other hand, predominat periods at CHB024 are changed from 1.3 sec indicated by a red arrow to 2.8 sec indicated by a blue arrow. This change to long-period is caused by the nonlinear behavior of the liquefaction. On the other hand, more longer waves of 4 or 5 seconds are originated in surface waves caused by the underground structure deeper than about 1km.



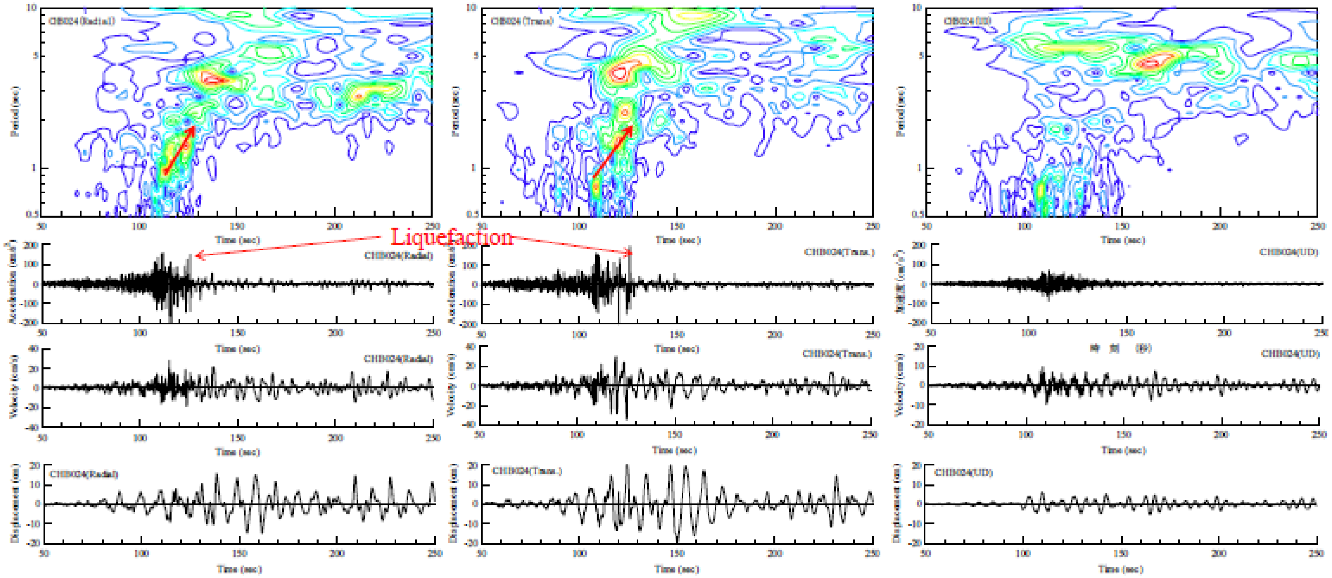
(a)radial (b)transverse (c)vertical

Fig. 10 Nonstationary spectra and waveforms of acc., vel. and dis.(CHB008, Urayasu)



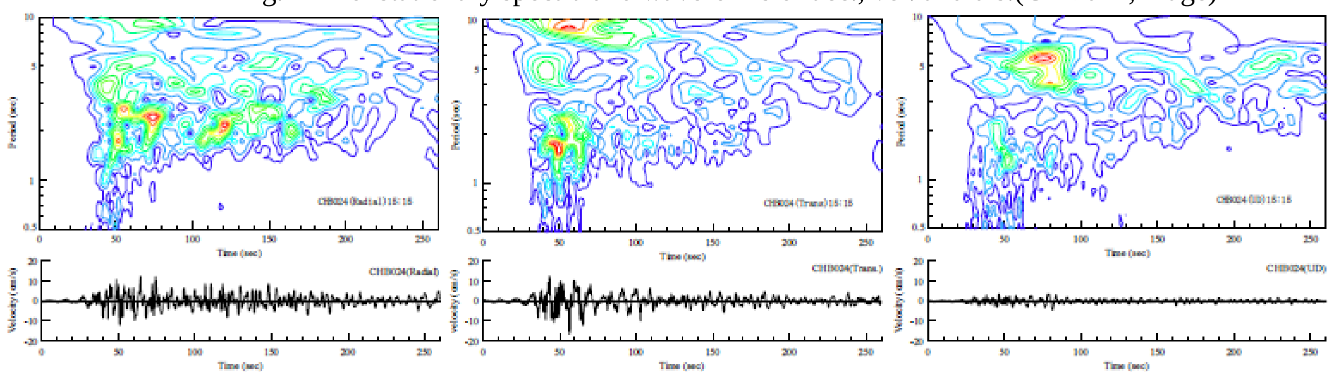
(a)radial (b)transverse (c)vertical

Fig. 11 Nonstationary spectra and waveforms of acc., vel. and dis.(CHB009, Chiba)



(a)radial (b)transverse (c)vertical

Fig. 12 Nonstationary spectra and waveforms of acc., vel. and dis.(CHB024, Inage)



(a)radial (b)transverse (c)vertical

Fig. 13 Nonstationary spectra and waveforms of vel. during the Aftershock (CHB024, Inage)

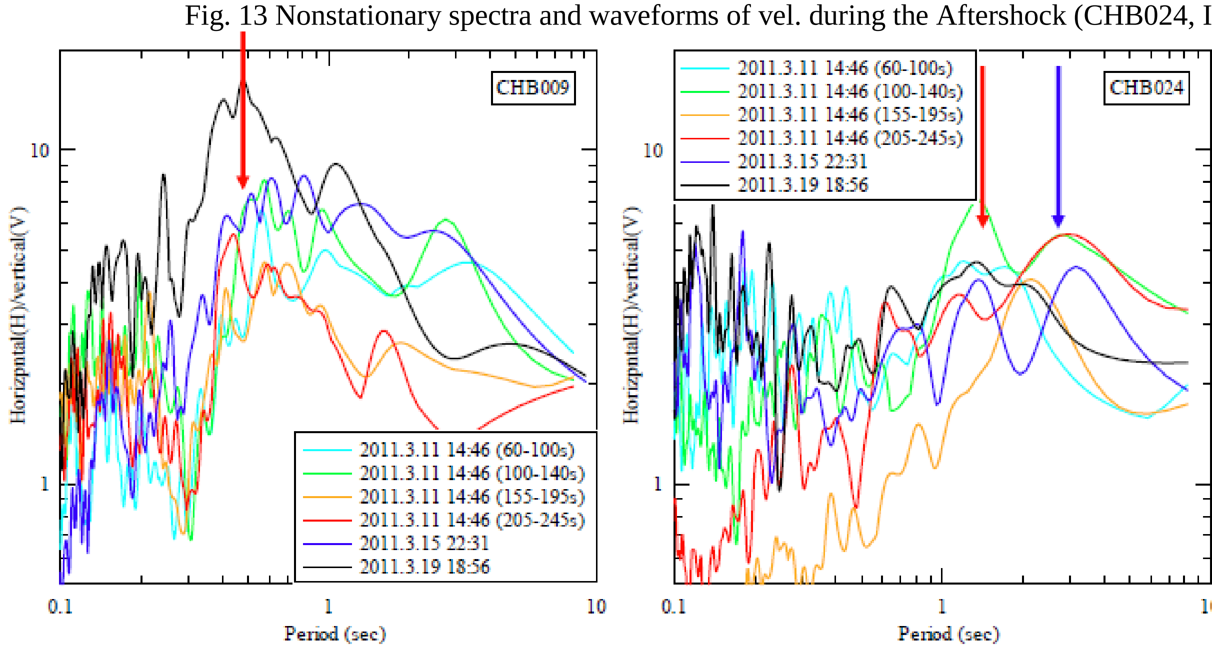
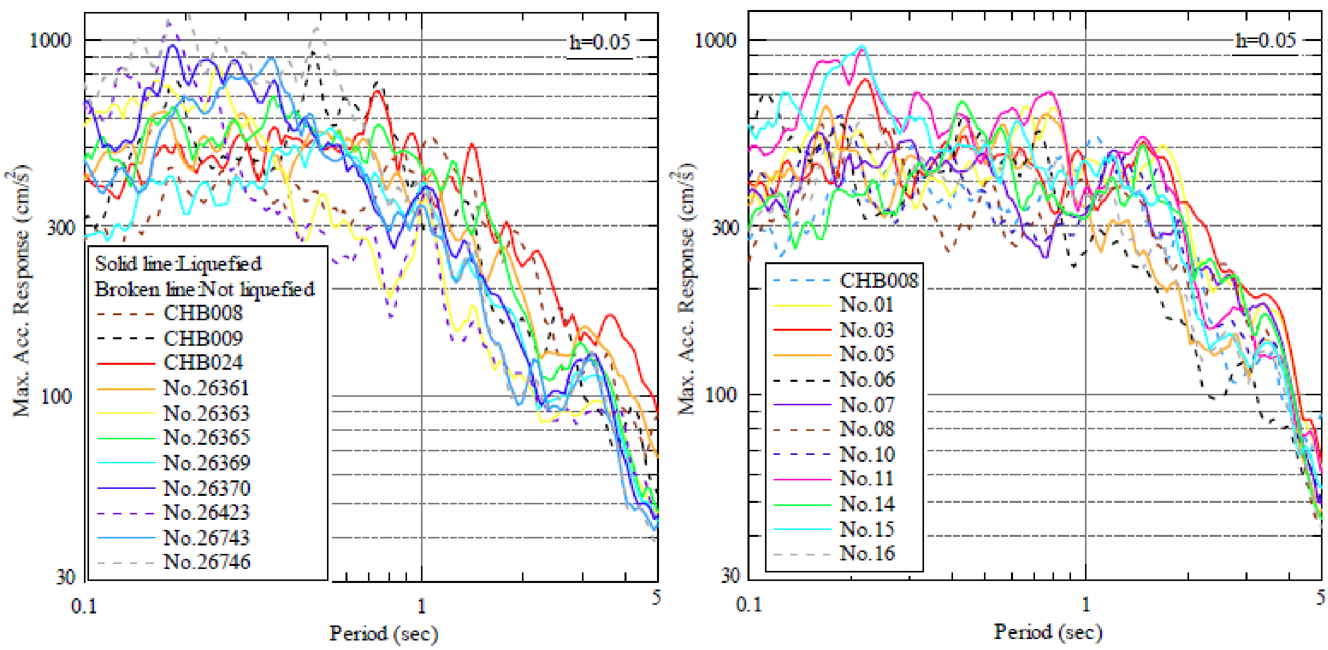


Fig. 14 Ratio of the Horizontal spectrum to Vertical spectrum (H/V)

Many earthquake ground motion records were observed at Chiba city and Urayasu city. Among them, acceleration response spectra at sites where the occurrence of liquefaction was investigated are shown in Figure 15. In Figure 15(a), the response at CHB024 in long-period is larger and that in short-period is smaller than other sites, and the component around 3 and 4 seconds is predominat. The same tendency can be seen at other liquefied sites. In Figure 15(b) at Urayasu city, a little less than 4 sec. is also predominat commonly and long-period component at liquefied sites is larger than non-liquefied sites.

The long-period shaking of liquefied ground, which was a kind of sloshing, was recorded by several inhabitants on video. One video taken just after the peak acceleration at Makuhari in Chiba City showed the strange cyclic heaving of a footway at a period of about 4 sec. The slow cyclic horizontal movement at the amplitude of about 15 cm was seen in another video taken two minutes after the peak acceleration in the Akemi district of Urayasu City.

Since the predominant wave at a period of about 4 sec. is common at both the mainshock and the aftershock, it can be estimated that it was generated by surface waves conserned with the deep ground structure. In addition, this wave was seen in the back part of the principal motion, so it can be assumed that it was generated at the edge of the plain in a boundary with the Shimofusa plateau or Hitachi plateau. On the other hand, the predominant period of surface soil became longer to 3 and 4 seconds because of small stiffness due to the liquefaction. Then, the predominant wave at 4 seconds vibrated sympathetically with the liquefied surface soil and the displacement amplitude became very large. The fact that this long-period wave were propagated repeatedly in the mainshock and the aftershock supports the mechanism of the heaving of a footway and the thrust of an alley as shown in Figure 4.



(a)Chiba city (b)Urayasu city

Fig. 15 Acceleration Response Spectra (h=5%) during the 2011 Great East Japan Earthquake

4. Conclusions

The duration of shaking during the 2011 Great East Japan Earthquake, a megathrust earthquake of magnitude Mw=9.0, was extremely long and was followed by big aftershocks. This remarkable shaking caused the following unusual liquefaction of the ground and liquefaction-induced damage to wooden houses, roads and lifelines.

(1) Liquefaction occurred in a wide area of reclaimed lands along Tokyo Bay though seismic intensities in the zones were not high, about 5- to 5+ in JMA scale, because of the long duration of the main shock and an aftershock 29 minutes later.

(2) The boiling of muddy water continued up to the aftershock, and the ground surface was covered by boiled water during the aftershock. Houses settled during the aftershock though the shaking amplitude was less than that during the main shock.

(3) Large horizontal displacement, a kind of sloshing of the liquefied ground, was induced due to the sympathetic vibration with the surface wave predominant at a period of about 4 sec. and the long duration of shaking after the occurrence of liquefaction and caused roads to thrust.

(4) By the same movement of the ground, pipes were displaced significantly in the horizontal direction, resulting the disconnection or breakage of joints. Manholes were sheared due to horizontal force.

5. Acknowledgement

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6. References

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