DAMAGE TO SEWAGE AND GAS FACILITIES INFLECTED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT
The 2011 Great East Japan Earthquake severely damaged sewage, gas, water and other lifeline facilities. Sewage pipes and manholes were damaged in 132 cities, towns and villages. Middle-pressure and low-pressure gas pipes were damaged at 20 and 773 sites, respectively. The damage resulted from soil liquefaction, the deformation of banked soils, strong shaking and a huge tsunami. Liquefaction in the Tokyo Bay area caused unique damage, such as the shear failure of manholes and the disconnection of pipe joints due to large horizontal displacement. In hill areas, pipes were damaged due to the failure or deformation of banked soils. A huge tsunami destroyed sewage plants near the coast of the Pacific Ocean.

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. The hypocentral region of this quake was about 500 km in length and 200 km in width. The quake was followed by a huge tsunami that destroyed many cities and killed and injured many people along the Pacific coast. Severe damage to many structures occurred in the Tohoku district of northeastern Japan and in the Kanto district surrounding Tokyo. As shown in Figure 1, seismic intensity in the affected area, as measured by the Japanese Meteorological Agency (JMA) scale, was 5 to 7, which corresponds to an intensity of 7 to 11 according to the Modified Mercalli (MM) scale. Many lifeline facilities, including water supply, sewage, gas, electric power and telecommunication facilities, were damaged due to liquefaction, the deformation of banked soils and strong shaking.

A huge tsunami hit many cities and caused severe damage along the coast of the Pacific Ocean. The maximum height was of this tsunami was 21.1 m. The Fukushima No.1 Nuclear Power Station was hit by a tsunami of 13.1 m in height. The emergency cooling system of the nuclear power plant was destroyed by the tsunami, causing very serious damage. Large parts of Japan have been plagued by radiation and a shortage of electricity ever since. The tsunami also damaged lifeline facilities.

LIQUEFIED SITES
Figure 2 is a map of the liquefied sites in the Kanto region (Kanto Regional Development Bureau, 2011). Because of their geomorphologic condition, the following sites liquefied:

a) Artificially reclaimed lands along Tokyo Bay and the Pacific Ocean
b) Filled lands on former ponds and marshes

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c) Sites excavated to obtain iron sand or gravel and then refilled.

Figure 3 is a map of the liquefied zones in the Tokyo Bay area. All the soil in the northern part of Tokyo Bay liquefied, but in the eastern and western parts of Tokyo Bay, liquefaction was observed only in spots. In the northern part of Tokyo Bay, the ground surface was covered with boiled sand around reclaimed lands in the Shinkiba area of Tokyo, in Urayasu City, Ichikawa City, Narashino City and western Chiba City. In contrast, boiled sand was observed only here and there in reclaimed lands in the Odaiba, Shinonome, Tatsumi, Toyosu and Seishin areas of Tokyo and in eastern Chiba City. The total liquefied area from Odaiba to Chiba City reached about 41 km². 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 soil liquefied.

Many seismic records were obtained in the Tokyo Bay area. Among them, accelerograms recorded by K-NET Inage in Chiba, shown in Figure 4, where boiled sand was observed, are very important because the liquefaction time can be judged from the recorded waves. 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 that many cycles of shear stress, say around 20 cycles over 110 sec., might have caused liquefaction at the Inage site. In Figure 4, time histories of velocity, displacement and non-stationary spectra estimated from the recorded acceleration are also shown. 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. Shaking continued at a long predominant period for a long time after the occurrence of liquefaction. 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. Slow cyclic horizontal movement at an amplitude of about 15 cm was seen in another video taken two minutes after the peak acceleration in the Akemi district of Urayasu City.
One of the authors visited Urayasu on the day after the earthquake and was surprised that a footway heaved and an alley thrust, as shown in Figure 5. The first impression was that the footway heaved due to uplift force on some buried pipes, such as sewage pipes. However, after that, strange thrusts and heavings of footways and alleys were also seen in 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 thrusts or heavings due to a kind of sloshing of liquefied ground, because shaking continued for a long time after the occurrence of liquefaction, as mentioned above. On the other hand, at Maihana in Urayasu, the thrust of an alley was observed though there was no such boundary, as shown in Figure 6. 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 appears that the heaving occurred at sites where the bottoms of the fill layer, in other words, the liquefied layer, was sloped. These imply 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 7.

LOCATIONS OF FAILED EMBANKMENTS

In Japan, many artificially reclaimed housing lots have been developed on hills and terraces in big cities, such as Tokyo and Osaka, from around 1960 to accommodate increasing populations. In the reclamation, the soils of hills are cut and banked in valleys, as schematically shown in Figure 8(1). Then, both cut and banked grounds are complicatedly distributed in housing lots. Figure 8(2) shows a schematic soil cross-section of banked land along a filled valley. The banked lands are apt to slide,
settle or deform during earthquakes if the filled soils are not compacted enough and/or the water table is high. Many banked lands have been damaged during recent earthquakes because they were built without considering their seismic stability.

The 2011 Great East Japan Earthquake caused very severe damage to filled grounds in many cities. The main damage occurred in Sendai, Shiroishi, Fukushima, Sukagawa, and Shirakawa cities and in Tokai Village, as shown in Figure 9. Figure 10 shows housing lots in Sendai taken three years before the earthquake. Many housing lots developed in the hills to the north, west, and south of Sendai City were severely damaged, as shown in Figures 11. According to an investigation conducted by the Sendai City Government about two month after the earthquake, there were 868 dangerous houses and 1,210 semi-dangerous houses among the 3,880 houses surveyed. However these numbers have not been confirmed. Figures 12 and 13 show typical damages to houses in Sendai City.

The authors conducted a detailed site investigation at Nankodai, where many banked lands were constructed for housing lots, to study the patterns of the damage. Based on the site investigation, the following six patterns were found (see Figure 14):
A. Failure of a banked slope: several houses at the top of the failed slope were damaged, as shown in Figure 15 (1).
B. Differential settlement between cuts and fills: many houses situated between cut ground and filled ground were torn, as shown in Figure 15 (2).
C. Strong shaking at stream confluences: several houses collapsed due to strong shaking at the confluence of three or four streams, as shown in Figure 15 (3).
D. Liquefaction at filled swamp: soils filling a former swamp liquefied and caused the settlement and inclination of several houses.
E. Liquefaction-induced flow of a gentle slope: the ground deformed as shown in Figure 15 (4), probably due to excess pore water pressure because the slope fill was sandy soil.
F. Liquefaction at a stream stricture: liquefaction was probably due to a high water table because a stream passed through a narrow area nearby. Several houses settled due to the liquefaction.

**DAMAGE TO SEWAGE FACILITIES**

According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), sewage pipes and manholes were damaged in 132 cities, towns and villages, as shown in Table 1 (Technical committee on measures to prevent damage to sewage facilities caused by earthquakes and tsunamis, 2012). Of 65,001 km of sewage pipes in the cities, towns and villages, 642 km were damaged. As shown in Figure 16, 65.9% of the damage to pipes was due to the liquefaction of sand fill and 24.5% was due to the liquefaction of both filled sands and the surrounding ground. Of the damage to manholes, 41.7% was due to the liquefaction of sand fill and 26.7% was due to the liquefaction of replaced soils and the surrounding ground. The damage due to the liquefaction of both filled sand and surrounding ground mainly occurred along Tokyo Bay, because liquefaction occurred in a wide area of reclaimed land, as mentioned before. Other causes of damage to sewage pipes and manholes were shaking, a tsunami, and the failure or deformation of fills.

Typical procedures for the construction of buried pipes and manholes in Japan are as follows:

i) ground is excavated using sheet piles or other retaining walls, ii) pipes or manholes are placed at the bottom of the ditch or holes, iii) the ditch or hole is filled with sand. Therefore, if the sand fill is loose and the water table is shallow, the replaced sand is apt to liquefy during earthquakes.
Many sewage manholes were uplifted during past earthquakes (Yasuda and Kiku, 2006). Figure 17 shows the mechanism of damage to pipes and manholes. The 2011 Great East Japan Earthquake also caused the uplift of manholes and pipes, as shown in Figure 18, due to the liquefaction of sand fill. However, a few pipes and manholes that had been restored with countermeasures after the 2008 Iwate-Miyagi-Nairiku Earthquake were not lifted during the 2011 Great East Japan Earthquake. These pipes and manholes had been restored by one of two measures proposed by the Technical Committee on Sewer Earthquake Countermeasures in 2005: i) fill ditches with gravel instead of sand, and ii) mix sand fill with cement. Moreover two other recently developed methods to prevent the uplift of manholes, illustrated in Figure 19, had been applied in some parts of the liquefied areas and successfully served their purpose.

Liquefaction occurred in a wide area of reclaimed land along Tokyo Bay, as described before. The most seriously damaged city was Urayasu City, where about 85% of the city area liquefied. Sewage pipes and manholes for waste water and rain water were severely damaged in a wide area. Urayasu City was equipped with 20.7 km of main sewage pipes and 191.5 km of branch sewage pipes. Most of the sites of damaged sewage pipes and manholes for waste water in Urayasu City, shown in Figure 20, were in zones where houses were severely damaged. Sewage pipes were deformed, cracked, broken and meandered, and joints were sheared or disconnected, as schematically shown in Figure 21. Many sewage manholes were cracked and sheared in the horizontal direction, as shown in Figure 22, and filled with muddy water, while a few manholes were lifted or slightly settled.

During past earthquakes, sand fill was liquefied and pipes and manholes were uplifted, as mentioned before, but during the 2011 Great East Japan Earthquake, both the filled sand and the surrounding soils were liquefied in Urayasu and other cities in the Tokyo Bay area. Moreover, large
amplitude of horizontal displacement continued at a long predominant period for a long time after the occurrence of liquefaction as mentioned above. The large horizontal displacement of liquefied ground had to have caused large cyclic compressional and tensile stress to the sewage pipes in horizontal direction, resulting in the disconnection of the pipe joints and the shear failure of the manholes, as schematically shown in Figure 21, allowing the influx of muddy water into the pipes and manholes. This muddy water may have prevented the uplift of the sewage pipes and manholes.

Houses built on banked soils and sewage and gas pipes inside the banked soils were damaged by the sliding or deformation of embankment fill. The open circles in Figure 14 show the locations of damaged sewage pipes and manholes at Nankodai in Sendai. These sites seem to be inside or at the boundary of fill. However, the mechanism of the damage to sewage pipes and manholes has not been studied.

Fourteen sewage plants located near the coast of the Pacific Ocean suffered severe damage due to the huge tsunami. Figure 23 shows the wall of a sewage plant in Sendai which was broken by the tsunami.

**DAMAGE TO GAS FACILITIES**

Gas pipes were also damaged in the Tohoku and Kanto regions. According to METI, high-pressure gas pipes were not damaged, but middle-pressure pipes were damaged at 20 sites and low-pressure main and branch pipes were damaged at 773 sites. Low-pressure pipes inside 7,132 houses were
Table 2 Summary of damage to low-pressure main and branch gas pipes (METI)

<table>
<thead>
<tr>
<th>Trigger to damage</th>
<th>Number of damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaking</td>
<td>618</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>103</td>
</tr>
<tr>
<td>Ground deformation</td>
<td>45</td>
</tr>
<tr>
<td>Slope failure</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>773</strong></td>
</tr>
</tbody>
</table>

damaged. Table 2 shows triggers of the damage to low-pressure main and branch pipes. Strong shaking damaged low-pressure pipes at 618 sites, liquefaction damaged pipes at 103 sites, ground deformation damaged pipes at 45 sites, and slope failure caused damage at 7 sites. Damage induced by liquefaction or ground deformation mainly occurred in the Tokyo Bay area and in Sendai City, where the damage to sewage pipes and manholes was also concentrated.

Figure 24 shows sites of gas pipe damage in Urayasu City, in the Tokyo Bay area. Gas holders, governor stations and high-pressure pipes were not damaged, and middle-pressure pipes were only slightly damaged. On the other hand, some low-pressure gas pipes were broken and muddy water filled the pipes to a length of 11 km, resulting in the shut-down of gas service for 8,631 homes.

In Sendai City, gas pipes in banked soils were damaged. Figure 25 shows the locations of damaged gas pipes at Nankodai. Although a detailed investigation has not been conducted, it seems that the damage occurred inside or at the boundaries of banked soils, just as did the damage to sewage pipes.
CONCLUSIONS

The 2011 Great East Japan Earthquake severely damaged sewage, gas and other lifeline facilities. Based on investigations by the authors and several technical committees, the following conclusions were derived:

(1) Sewage and gas facilities were severely damaged by liquefaction in lowland areas, the deformation of banked lands in hills, a tsunami and strong shaking.

(2) Liquefaction caused two types of damage to sewage pipes and manholes: i) lifting due to the liquefaction of replaced soils, and ii) the shear failure of manholes and disconnection of pipe joints due to the liquefaction of replaced soils and the surrounding ground.

(3) The horizontal displacement of the liquefied soil around the pipes in the Tokyo Bay area caused by the 2011 earthquake must have been large because a wide area liquefied and shaking must have continued for a long time after the occurrence of liquefaction. The large horizontal displacement of liquefied ground had to have caused the disconnection of the pipe joints and the shear failure of the manholes.

(4) The banked lands at many housing lots in hills failed or deformed. The houses and their sewage and gas pipes were damaged inside or at the boundaries of the banked lands.

(5) Sewage plants located near the coast of the Pacific Ocean were severely damaged due to a huge tsunami.

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REFERENCES


