LIQUEFACTION-INDUCED DAMAGE TO STRUCTURES DURING THE 2011 GREAT EAST JAPAN EARTHQUAKE

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The 2011 Great East Japan Earthquake caused liquefaction in many places in the Tohoku and Kanto regions. Because of some areas’ geomorphologic condition, liquefaction occurred in artificially reclaimed lands along Tokyo Bay and the Pacific Ocean, filled lands on former ponds and marshes, and sites of excavation to get iron sands or gravels which had been filled. The most serious damage occurred in Urayasu City, near Tokyo. About 85% of the Urayasu City area liquefied and wooden houses, roads and buried pipes were damaged. However, buildings and bridges supported by piles were not damaged even though the ground around them liquefied. In the Tohoku and Kanto regions, river dikes were damaged at about 2,100 sites, mainly because of the liquefaction of the foundation ground and/or embankments. Sewage pipes and manholes sustained two types of damage: i) lifting due to the liquefaction of replaced fill soils, and ii) the shear failure of manholes and disconnection of pipe joints due to the liquefaction of filled soils and the surrounding ground. Oil tank yards, harbor structures and a tailings dam were also damaged.

Key Words : liquefaction, sandy soil, road, river dike, buried pipe

1. INTRODUCTION

Soil liquefaction during earthquakes causes severe damage to many structures. Buildings, tanks, and embankments settle because the soil beneath them loses strength. Underground tanks and buried pipes are lifted because the ground becomes like a liquid and floats owing to buoyancy. Quay walls move towards the sea due to increased earth pressure on them. Piles bend by the horizontal seismic inertial force of superstructures because their bearing capacity is reduced. Moreover, if the ground faces a waterfront or has a gentle slope, liquefaction tends to cause it to flow, often inducing extreme damage, such as the collapse of pile foundations.

During the 2011 Great East Japan Earthquake, soil liquefaction occurred in the Tohoku region of northeastern Japan and in the Kanto region surrounding Tokyo because the earthquake was huge, with a magnitude of $M_w=9.0$. Liquefaction occurred in a wide area of reclaimed land along Tokyo Bay, though the epicentral distance was very large, about 380 to 400 km. Large amounts of boiled sand, large settlements and a kind of sloshing of liquefied grounds were observed in the Tokyo Bay area. Many houses, roads, lifeline facilities, and river dikes were severely damaged by soil liquefaction1) 2). The most seriously damaged city was Urayasu City, where about 85% of the city area liquefied. Some port and harbor facilities, tank yards, electric power stations and tailings dams were also damaged in the Tohoku and Kanto regions. However, many new bridges, buildings, tanks, port and harbor facilities, etc. escaped damage because these structures had been designed to withstand the effect of liquefaction. Old structures which had not been originally designed to...
withstand the effect of liquefaction but had been repaired to prevent liquefaction-induced damage were not damaged either. In this paper, liquefaction-induced damage to structures during the 2011 Great East Japan Earthquake is introduced by focusing on the damage in Urayasu City.

2. BRIEF HISTORY OF THE DESIGN METHODS FOR LIQUEFACTION IN JAPAN

In 1964, the Niigata and Alaska earthquakes inflicted huge damage on buildings, bridges and other structures by liquefying loose sandy soils. After these earthquakes, studies on liquefaction began to be widely carried out using laboratory cyclic shear tests, shaking table tests, and site investigations and analyses. Based on these studies, methods for the prediction of liquefiable layers, the design of structures in liquefied grounds and measures to prevent liquefaction were developed. In Japan, since 1970, design methods for liquefaction have been introduced in the seismic design codes for port and harbor facilities, highway bridges, railway structures, and buildings, as shown in Table 1. Later design methods were introduced for almost all important facilities, such as oil tanks, LNG tanks, high-pressure tanks, water pipes, sewage pipes and gas pipes. However, for water and sewage facilities, these design methods were applied only to major pipes in the early stage, and then gradually applied to normal pipes.

Countermeasures against liquefaction have also been developed. During the 1964 Niigata earthquake, many oil tanks settled due to liquefaction. However, some tanks were not damaged because their foundation ground had been compacted by vibro-flotation. This was the first time that the effectiveness of ground compaction against liquefaction was recognized. After this, many other kinds of remediation methods were developed in Japan, including sand compaction piles and gravel drains. These remediation methods were summarized in a book by the Japanese Geotechnical Society (JGS) in 1993 in Japanese, which was translated into English in 1998.

Recently, almost all new structures have been designed to prevent damage due to liquefaction. However, many structures remain which were constructed before their seismic design codes considered liquefaction, and many small structures are still designed without consideration of the effect of liquefaction. Fig.1 summarizes the earthquakes that caused liquefaction-induced damage to structures from 1964 to 2011, when the Great East Japan Earthquake occurred. As shown in Fig.1, liquefaction occurred during 25 earthquakes in those 47 years in Japan.

During the 2011 Great East Japan Earthquake, many wooden houses were damaged due to liquefaction, though no one died as a result. According to the Ministry of Land, Infrastructure, Transport and Tourism, about 27,000 houses were damaged due to liquefaction. This large number of houses suffered damage because no design method for liquefaction has been introduced for wooden houses, since liquefaction-induced settlement of houses does not cause serious problems or threats to inhabitants, such as loss of life. Many of the buried structures and river dikes that were damaged had been constructed before liquefaction was considered in their seismic design codes.

On the other hand, many structures, such as elevated bridges, buildings, high-pressure gas pipelines,

<table>
<thead>
<tr>
<th>Design codes and standards</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design standard for port and harbour facilities</td>
<td>1970</td>
</tr>
<tr>
<td>Seismic design manual for highway bridges</td>
<td>1972</td>
</tr>
<tr>
<td>Design criteria of building foundation structures and commentaries</td>
<td>1974</td>
</tr>
<tr>
<td>Design standard for railway structures, foundation and retaining wall</td>
<td>1974</td>
</tr>
<tr>
<td>Notification specifying particulars of technical standards concerning control of hazardous materials</td>
<td>1974</td>
</tr>
<tr>
<td>Guideline for remedial measures of water works facilities against earthquakes</td>
<td>1979</td>
</tr>
<tr>
<td>Specification of construction of taking dams and commentary</td>
<td>1980</td>
</tr>
<tr>
<td>Recommendation practice for LNG in ground storage</td>
<td>1981</td>
</tr>
<tr>
<td>Notification specifying particulars of technical standards concerning control of hazardous materials</td>
<td>1981</td>
</tr>
<tr>
<td>Seismic design standard of land reclamation for Agriculture (Draft)</td>
<td>1984</td>
</tr>
<tr>
<td>Design manual for housing sites</td>
<td>1984</td>
</tr>
<tr>
<td>Design manual for common utility ducts</td>
<td>1985</td>
</tr>
<tr>
<td>Highway earthquake series, manual for self-ground remediation</td>
<td>1986</td>
</tr>
<tr>
<td>Technical guidelines for seismic design of nuclear power plants</td>
<td>1987</td>
</tr>
<tr>
<td>Design method of high-pressure gas pipeline for liquefaction</td>
<td>2001</td>
</tr>
</tbody>
</table>

Fig.1 Sites of soil liquefaction in Japan caused by earthquakes from 1964 to 2011.
and oil tanks, were not damaged, even though severe soil liquefaction occurred, because these structures had been designed to resist liquefaction damage by incorporating pile supports or improving the foundation soil.

3. GEOMORPHOLOGICAL FEATURES OF LIQUEFIED SITES

Liquefied sites in the Tohoku and Kanto regions were investigated by many members of the Japan Society for Civil Engineering (JSCE), the JGS, and others. 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. Fig.2 is a map of the liquefied sites in the Kanto region. 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
c) Sites excavated to get iron sands or gravels and then refilled.

In addition, embankments and foundations of river dikes and refilled soils for sewage pipes liquefied.

Liquefaction occurred along the Pacific coast of the Tohoku region, but the liquefied sites were obscured by a huge tsunami that hit the coastal area about 30 minutes after the earthquake. According to several photos and videos taken after the earthquake and before the tsunami, liquefaction may have occurred in natural ground, as well as in reclaimed land. In higher ground unaffected by the tsunami, filled soils at many housing lots and a tailings dam liquefied.

4. EFFECT OF LIQUEFACTION ON STRUCTURES IN URAYASU CITY

(1) Liquefied area in Tokyo Bay area

Fig.3 is a map of the liquefied zones in the Tokyo Bay area. The whole area of 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 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 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 city liquefied.

The epicentral distance of the liquefied area in Tokyo Bay is very long, around 400 km. However, the distance from the boundary of the rupture plane is...
only 110 km because the rupture plane is very wide.

(2) History of reclamation and soil in Urayasu City

The reclamation of coastal areas in Tokyo Bay started in the seventeenth century and accelerated with an increase in population. The history of reclamation work in Urayasu City is summarized in Fig. 4. Urayasu City is divided into three towns, Motomachi, Nakamachi and Shinmachi, which mean old, middle and new towns, respectively. The ground of Motomachi formed naturally at an estuary of Edo River. On the other hand, zones A, B and C in Nakamachi were reclaimed from 1965 and zones D, E and F in Shinmachi were reclaimed from 1972. The area of each zone is 1.0 to 3.5 km², and the total area of Nakamachi and Shinmachi is 14.36 km², which is about 85% of the area of Urayasu City.

Four months after the earthquake, a technical committee chaired by Prof. K. Ishihara was organized by the Urayasu City Government to study the mechanism of liquefaction-induced damage and restoration works. The committee conducted detailed soil investigations, laboratory tests and analyses, and reported valuable results. The following is a brief summary of the report.

Fig. 5 shows a soil cross-section along the line Urayasu D-D’ in Figs. 3 and 4 through Motomachi, Nakamachi and Shinmachi. In the reclaimed zone, a filled layer of mainly hill sand (B) and a filled layer of dredged sandy soil (F) with low SPT N-values averaging 5.46 are deposited with a thickness of several meters. Though layer F had to be liquefied, the fines content of layer F is very large, with an average value of about 44%, and very scattered from \( F_C = 0\% \) to 100%, as shown in Fig. 6. An alluvial sand layer (AS) with an average SPT N-value of 12.9 underlies the filled layer. The average fines content of layer AS is 30.9%. A very soft alluvial clay layer (Ac) is deposited under the AS layer with a thickness of 10 to 40 m, increasing in thickness as it approaches the sea. A diluvial (Pleistocene) dense sandy layer (Ds) underlies the alluvial clay layer. The water table is shallow, averaging 1 to 2.5 m below ground level (G.L.).

Urayasu City contains light structures, such as wooden houses, and heavy structures, such as high-rise buildings and elevated bridges. These heavy structures are supported by long piles which mainly penetrate to the depth of the diluvial dense layer.

(3) Zones of structural damage

Fig. 7 shows the areas of Urayasu City where liquefaction damaged sewage facilities, roads and houses. Liquefaction occurred only in Nakamachi and Shinmachi, as Motomachi is built on natural land. In Motomachi an alluvial sand (As) layer is deposited just under the water table, as shown in Fig. 5. If the As layer had liquefied, sand boils should have appeared. However, no sand boils, nor damage to houses and lifeline facilities, occurred. Therefore, it can be estimated that the As layer basically was not liquefied by the 2011 Great East Japan Earthquake, though some loose parts of the layer might have
liquefied and some parts of the dredged sandy soil under the water table might have liquefied in Nakamachi and Shinmachi.

Sewage pipes, manholes, roads and houses were damaged in the liquefied areas, but the severity of damage to roads and houses varied from place to place.

(4) Accelerations during main shock and aftershock

The duration of shaking in the 2011 Great East Japan Earthquake was extremely long, and the main shock was soon followed by a big aftershock. Surface acceleration during the main shock was not high, around 160 Gal. Fig.8 shows the accelerographs and velocities recorded during the main shock and the aftershock by K-NET in Urayasu on ground where liquefaction did not occur.

Some inhabitants of Urayasu City observed the boiling of muddy water immediately after the main shock, while others saw spouts of muddy water five to nine minutes after the main shock. Surprisingly, some inhabitants testified that boiling did not occur during the main shock but occurred during the aftershock. Some excess pore-water pressure may have built up during the main shock, causing complete liquefaction during the aftershock. It is impossible to evaluate the liquefaction time, but it must have differed by place because of the long duration of the main shock and the subsequent large aftershock. Shaking continued for a long time after the occurrence of liquefaction.

(5) Damage to flat roads

As described in Table 2, there are four grades of planar roads in Urayasu City: national roads, pre-
fectural roads, main city roads and normal city roads. The total length of damaged roads amounted to about 80 km. These roads were designed without considering liquefaction because no seismic design codes which consider liquefaction have been developed for flat roads. Liquefaction caused several phenomena to interrupt traffic:

i) much muddy water boiled onto roads (see Fig.9);
ii) road asphalt heaved, was thrusted or was deformed into waves at many sites (see Fig.10);
iii) many small road cave-ins occurred several months after the earthquake.

(6) Damage to river and sea walls

Three sides of Urayasu City face Tokyo Bay and are protected by sea walls. Two rivers, the Sakai River and the Miake River, transverse Urayasu City from northwest to southeast and are protected by river walls. These sea and river walls were not designed to withstand liquefaction damage because reclamation work for the walls started only a few years after the 1964 Niigata Earthquake, when liquefaction was first recognized. Though many sea and river walls are found in the liquefied area, only a few walls were damaged, as shown in Fig.4. These sea and river walls slightly expanded and settled. Fig.11 shows the damaged concrete river wall at Sakai river in Urayasu City, and Fig.12 shows a cross-section of this wall.

During the 1995 Hyogoken-nambu Earthquake, many caisson quay walls and sea walls moved and tilted toward the sea in the liquefied area, resulting in large lateral flows of the ground behind the walls. The failure of the quay wall is a complex dynamic phenomenon. To explain from the point of view of the design, the failure process can be summarized as follows: i) a strong inertial force due to very high acceleration, ii) a decrease in shear strength due to an increase in excess pore-water pressure in the replaced sand beneath the caisson walls, and iii) an increase in earth pressure due to a rise in excess pore-water pressure in the ground behind the wall. In contrast, only a few sea and river walls moved and tilted in Urayasu and other cities along Tokyo Bay during the 2011 Great East Japan Earthquake. The reasons for the difference in damage to these walls caused by the two earthquakes are uncertain, but they may be the different wall types and strengths, different soil conditions, different slopes of the ground behind the walls, the depth of liquefied soil and different accelerations.

(7) Damage to lifeline structures

Lifeline facilities for water, sewage, gas, electric power and telegraphs were severely damaged in the liquefied area. Though seismic design codes for these

<table>
<thead>
<tr>
<th>Table 2 Extent of road damage in Urayasu City6).</th>
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<tbody>
<tr>
<td>Length (km)</td>
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<td>-------------</td>
</tr>
<tr>
<td>National road</td>
</tr>
<tr>
<td>Prefectural road</td>
</tr>
<tr>
<td>City main road</td>
</tr>
<tr>
<td>City normal road</td>
</tr>
</tbody>
</table>

Fig.9 Cars stuck in boiled muddy water in Urayasu City6).

Fig.10 Thrusted road pavement in Urayasu City6).

Fig.11 Moved and settled wall along Sakai River in Urayasu City6).
facilities started to consider the effect of liquefaction from about 1980, as shown in Table 1, many lifeline facilities in Urayasu City were constructed before that date. So, many facilities were damaged due to liquefaction. Detailed assessments of damage to buried pipes have been excavated and permanently restored.

Leakage occurred at 608 sites along water pipes, and water service for 33,000 households was stopped. Water pipes were broken at 122 of the leakage sites, and joints were pulled out or sheared at 366 sites.

Sewage pipes and manholes for waste water and rain water were severely damaged in a wide area. Urayasu City was served by 20.7 km of main sewage pipes and 191.5 km of branch sewage pipes. Of these pipes in Nakamachi and Shinmachi, 20% and 14%, respectively, were damaged, whereas no pipes were damaged in Motomachi, as summarized in Table 3. Fig. 13 shows the sites of damaged waste water pipes and manholes. Sewage pipes were deformed, cracked, broken and meandered, and joints were sheared or disconnected, as shown in Fig. 14 (1).

Table 3 Extent of damage to public waste water pipes and manholes in Urayasu City6).

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Motomachi</th>
<th>Nakamachi</th>
<th>Shinmachi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (km)</td>
<td>84.2</td>
<td>94.4</td>
<td>33.6</td>
</tr>
<tr>
<td>Damaged length (km)</td>
<td>0</td>
<td>19.2</td>
<td>4.6</td>
</tr>
<tr>
<td>Damage rate (%)</td>
<td>0</td>
<td>20</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manhole</th>
<th>Number</th>
<th>2,348</th>
<th>2,799</th>
<th>1,069</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damaged number</td>
<td>0</td>
<td>328</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>Damage rate (%)</td>
<td>0</td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>
Muddy water seeped into the damaged pipes for 127.2 km and closed pipes completely for about 60 km. Many sewage manholes were cracked and sheared in a horizontal direction and filled with muddy water, as shown in Fig. 14 (2), while a few manholes were lifted or slightly settled, as shown in Fig. 14 (3). Muddy water filled almost all manholes in Nakamachi and Shinmachi. It took 34 days to restore these damaged pipes and manholes provisionally.

Shear damage to manholes had not occurred during past earthquakes in Japan. Many sewage manholes were lifted but not sheared during the 1993 Kushiro-oki earthquake, the 2003 Tokachi-oki earthquake and the 2004 Niigataken-chuetsu earthquake. During the construction of the manholes and pipes, the ground was excavated to a width of about 2 m. After placing the manholes and pipes, the excavated area was filled with sand. During past earthquakes, only the fill soils were liquefied, but during the 2011 Great East Japan Earthquake, both the fill soils and the surrounding soils were liquefied in Urayasu. Therefore, the horizontal displacement of the liquefied soil around the pipes in Urayasu caused by the 2011 earthquake must have been larger than the horizontal displacement caused by previous earthquakes. Moreover, as the main shock of the 2011 earthquake was very long and was followed by a big aftershock, 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, allowing the influx of muddy water into the pipes and manholes.

In gas facilities, 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.

Buried cables for electric power distribution were damaged at six sites. Manholes for telegraph lines were sheared similar to the sewage manholes. Moreover, electric and telegraph poles seriously settled and tilted here and there.

A steel water tank for emergency use buried to a depth of G.L.-2.4 m was lifted, as shown in Fig. 15, though the tank did not break. The tank is 3.0 m in diameter, 15.1 m in length, 100 m³ in capacity and fixed with belts to prevent uplift; the belts must have failed.

(8) Damage to houses

According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), about 27,000 wooden houses in Japan were damaged due to liquefaction caused by the 2011 Great East Japan Earthquake. Strip footing foundations or mat foundations are used for houses in Japan. In the design of wooden houses, liquefaction has not been considered, whereas the design code for other buildings has considered liquefaction since 1974, as shown in Table 1. This is the main reason such a large number of houses were damaged. In contrast, some houses supported by steel piles or cement-mixed soil piles penetrating to the depth of the non-liquefied layer did not settle.

In Urayasu City, severely damaged houses were located in the zones shown in Fig. 7. Many houses settled and tilted, though they suffered no damage to walls and
windows, as shown in Fig.16. In the greatly tilted houses, inhabitants felt giddy, sick and nauseated, and found it difficult to live in their houses after the earthquake. In May 2011, the Japanese Cabinet announced a new standard for the evaluation of damage to houses based on two factors, settlement and inclination. A new class of “large-scale half collapsed house” was also introduced, and houses tilted at angles of more than 1/20, of 1/20 to 1/60, and of 1/60 to 1/100 were judged to be totally collapsed, large-scale half collapsed and half collapsed houses, respectively, under the new standard. The number of damaged houses in Urayasu City by the new standard is listed in Table 4. The number of totally collapsed, large-scale half collapsed, half collapsed partially damaged and undamaged houses in Urayasu City was 10, 1,509, 2,102, 4,848 and 963, respectively, as of Sept. 3, 2011. According to a previous study on the non-uniform settlement of houses\(^8\),\(^9\), several factors affect such settlement. Among them, the effect of adjacent houses was dominant in the Abehikona housing lot during the 2000 Tottori-ken-seibu Earthquake\(^10\). A similar tendency was observed in the Tokyo Bay area. If two houses are close to each other, they tilt toward each other, and if four houses are close together, they tilt toward their center point\(^8\),\(^9\) as shown in Fig.16.

Even in liquefied areas, several zones did not liquefy or suffer damage to houses because the ground in these zones had been improved. One example is a housing lot in Irifune where sand compaction piles (SCPs) were installed in the foundations of mainly three-story houses to increase the bearing capacity and to prevent liquefaction, and gravel drains (GDs) were installed in the foundations of mainly two-story houses to mitigate liquefaction\(^11\). Each type of building had a spread foundation (continuous foundation) supported by nodular piles 8 m long. Following the earthquake, sand boils were observed in unimproved areas around the housing lot. However, no sand boils were seen within the improved area and no damage occurred to buildings constructed on ground improved by either the SCP method or the GD method.

(9) Damage to heavy structures supported by piles

Many road and railway bridges supported by piles were not damaged, though liquefaction occurred around the piles. Fig.17 shows an elevated bridge on the Keiyo Railway Line which is supported by pre-stressed concrete (PC) and steel and concrete composite (SC) piles, as illustrated in Fig.18. In the design of the pile foundation, liquefaction was assumed to be probable and the lateral bearing capacity of the liquefiable layer, from the water level to G.L. -10 m, was assumed to be zero\(^12\). Thus, SC piles, which are stronger than PC piles, were installed to a depth of -10 m.

There are many buildings supported by piles in the liquefied area. These buildings were not damaged, but the inhabitants of some apartment buildings were forced to live in inconvenient conditions for weeks because of the shutdown of lifeline facilities and because of ground settlement at the entrances of their apartment houses. At the fire station shown in Fig.19, ladder trucks could not enter the fire station due to the settlement of the road in front of the station.

During the 1995 Hyogoken-nambu Earthquake, many piles for road bridges and apartment buildings were damaged due to liquefaction in Kobe City. In contrast, no damage occurred to road bridges and apartment buildings with similar pile foundations in Urayasu and other cities in the Tokyo Bay area. This difference in damage may be due to the larger amplitude of shaking in Kobe, where the recorded accelerations were about three times the accelerations recorded in the Tokyo Bay area.

Table 4 Number of damaged houses in Urayasu City under old and new standards (Counted on Sept. 3, 2011).

<table>
<thead>
<tr>
<th>Grade of damage</th>
<th>Number of houses</th>
<th>Old standard</th>
<th>New standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totally collapsed</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Large-scale half collapsed</td>
<td>0</td>
<td>1,509</td>
<td></td>
</tr>
<tr>
<td>Half collapsed</td>
<td>33</td>
<td>2,102</td>
<td></td>
</tr>
<tr>
<td>Partially damaged</td>
<td>7,930</td>
<td>4,848</td>
<td></td>
</tr>
<tr>
<td>No damage</td>
<td>1,028</td>
<td>963</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8,999</td>
<td>9,432</td>
<td></td>
</tr>
</tbody>
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Fig.16 Settled and tilted houses in Urayasu City.
5. LIQUEFACTION-INDUCED DAMAGE TO SEVERAL STRUCTURES IN TOHOKU AND KANTO REGIONS

(1) Damage to river dikes
River dikes settled and slid seriously at many sites in the Tohoku and Kanto regions. According to the Tohoku and Kanto Regional Development Bureaus of the MLIT, there were 1,195 sites of dike damage in the Tohoku region and 939 sites in the Kanto region. Most river dikes in these regions were designed and constructed without considering liquefaction. In the Tohoku region, a few dikes which had been damaged during earthquakes in 1978 and 2003 and restored to prevent liquefaction-induced damage suffered no damage from the 2011 Great East Japan Earthquake. After this earthquake, technical committees were organized by the two regional development bureaus to ascertain the mechanism of failure and select appropriate restoration methods.

In the Kanto region, dikes along the Tone, Kokai, Kinu, Hinuma, Naka and other rivers were damaged, as shown in Fig.20. The types of damage included settlement, slides, longitudinal cracks and transverse cracks. Serious damage occurred at 55 sites. The mechanism of the damage at the seriously damaged sites was studied based on soil investigation. It was concluded that 51 sites suffered damage triggered by liquefaction. As shown in

Fig.17 Undamaged elevated bridge on the Keiyo Railway Line at Shin-Urayasu Station.

Fig.18 Diagram of pile foundation of Keiyo Railway Line. Upper pile: SC pile, Lower pile: PC pile

Fig.19 Road subsidence in front of a fire station.

Fig.20 Sites of river dike damage in the Kanto region (modified from MLIT).

Fig.21 Settled river dike along the right bank of Tone River.
Fig. 22, there were three patterns of liquefied soil: 1) the foundation ground liquefied, 2) the lower part of the embankment liquefied, and 3) both foundation ground and embankment liquefied. In the latter two types, the water tables inside the embankments were higher than the water tables in the surrounding ground. In the restoration work, several appropriate methods were selected in accordance with the type and severity of damage to prevent damage during future earthquakes, as shown in Fig. 23.

(2) Damage to sewage pipes and manholes
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\textsuperscript{(14)}. As shown in Fig. 24, 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, as shown in Fig. 25, because liquefaction occurred in a wide area of reclaimed land, as mentioned before.

Most of the damaged pipes and manholes were constructed without consideration of liquefaction. A few pipes and manholes that had been restored with

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<td>Embankment + ground</td>
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<td><img src="image6" alt="Schematic of Drainage and Sheet Pile" /></td>
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Fig. 23 Diagram of methods to restore damaged river dikes in the Kanto region (modified from MLIT\textsuperscript{(15)}).

Fig. 24 Causes of damage to sewage pipes in the 132 damaged cities, towns and villages\textsuperscript{(14)}.

Fig. 25 Areas where two patterns of damage to sewage pipes and manholes dominated\textsuperscript{(14)}.

Fig. 26 Diagrams of successful measures for preventing the uplift of existing manholes\textsuperscript{(14)}.
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 the Sewer Earthquake Countermeasures in 2005: i) fill ditches with gravel instead of sand, and ii) mix the filled sand with cement.

Two other recently developed methods to prevent the uplift of existing manholes, illustrated in Fig.26, had been applied in some parts of the liquefied areas and successfully served their purpose.

(3) Damage to plants

There are many electric power plants, oil tank yards, factories and warehouses in the liquefied areas along the coasts of Tokyo Bay and the Pacific Ocean. Fig.27 shows a tilted oil tank yard fence. The extent of damage to plants is still unknown because most of the plants belong to private companies and site surveys are difficult to undertake. However, serious damage, such as the burning of oil tanks, did not occur in the liquefied areas. Most likely, the main reason for this lack of serious damage is that the important facilities, such as oil tanks and electric power plants, were designed based on seismic design codes that considered liquefaction and required the use of appropriate pile foundations or soil improvement. Many old oil tanks constructed before liquefaction was considered in seismic design codes had been strengthened against liquefaction by special measures, such as surrounding the tanks with sheet piles to prevent liquefaction-induced settlement.

(4) Damage to port and harbor structures

There are many ports and harbors along the coasts of the Pacific Ocean and Tokyo Bay. No serious damage was inflicted on ports and harbors in the liquefied areas along Tokyo Bay. Along the Pacific coast, it is not easy to judge whether damage occurred due to liquefaction or not because a huge tsunami washed away all traces of liquefaction. Sugano reports that obvious liquefaction-induced damage occurred at two ports, Souma Port and Onahama Port, where the corners of quay walls moved toward the sea. At Onahama Port, an apron behind a quay wall settled below the rails for cargo loaders.

At Sendai Airport, an underpass road and an underground conduit had been constructed beneath the tarmac at four points. For their construction, the ground had been excavated. After their construction, the excavated area was filled with sand. Subsequently, special techniques to prevent liquefaction, i.e., compaction grouting, and high-pressure injection, were applied to the sand fill at three of these points. No liquefaction accompanying the Great East Japan Earthquake occurred at these three points. However, at the fourth point, which had not been improved, the tarmac settled.

(5) Damage to a tailings dam

Three abandoned tailings dams failed in the Tohoku and Kanto regions. The Kayakari tailings dam built by Ohya Mining, located near Kesen-numa City in Miyagi Prefecture, failed due to the liquefaction of gold slime, as shown in Fig.28. A cross-section of the failed slope is shown in Fig.29. Slime from the failed slope flowed down a small river and destroyed a house.

Fig.27 Tilted oil tank yard fence along the Pacific Ocean coast.

Fig.28 Liquefied and failed slope of Kayakari tailings dam.

Fig.29 Cross-section of failed slope at Kayakari tailings dam.
The Kayakari tailings dam was constructed by the inner filling method and finished in 1966. After the Mochikoshi tailings dam failed due to liquefaction during the 1978 Izuohshima-kinkai Earthquake, liquefaction consideration was introduced in the design code for tailings dams in 1980. Then, the probability of liquefaction-induced damage at many tailings dams was estimated by conducting soil investigations and tests. The Kayakari tailings dam was one of those examined, and the examiners concluded that there was little or no probability of such damage. However, the seismic intensity that hit the Kayakari tailings dam during the Great East Japan Earthquake was fairly higher than the examined intensity.

6. CONCLUSIONS

Liquefaction-induced damage to structures during the 2011 Great East Japan Earthquake has been described based on site investigations conducted by the authors and others, and the following conclusions are derived:

1) Because of their geomorphologic condition, artificially reclaimed lands along Tokyo Bay and the Pacific Ocean, filled lands on former ponds and marshes, and sites of excavation to get iron sands or gravels that had been refilled, liquefied.

2) In Urayasu City, where about 85% of the city area liquefied, wooden houses, flat roads and buried pipes were seriously damaged due to liquefaction, whereas buildings and bridges supported by piles were not damaged even though the ground surrounding them liquefied.

3) River dikes were damaged at about 2,100 sites, mainly because of the liquefaction of the foundation ground and/or embankments.

4) Sewage pipes and manholes sustained two types of damage: i) lifting due to the liquefaction of fill soils, and ii) the shear failure of manholes and pull-out of pipe joints due to the liquefaction of fill soils and the surrounding ground.

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