A study of earthquake-caused liquefaction: the case of Urayasu City

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Abstract

Soil liquefaction describes a phenomenon whereby saturated soil loses a substantial part of its strength and stiffness in response to an applied stress, usually from earthquake shaking or another sudden change in stress conditions, causing it to behave like a liquid. Liquefaction caused by the Great East Japan Earthquake of 2011 occurred on reclaimed land around the Tokyo Bay area. Urayasu City suffered extensive damage from liquefaction triggered by the earthquake, and effects of the disaster are still ongoing. This paper describes some remarkable damage to structures produced by liquefaction induced by the earthquake and indicates the potential for liquefaction using current determination methods on published soil profiles and N values from standard penetration tests, and introduces a measurement method (the grid-form underground wall method) that will be adopted in Urayasu City. The authors also conducted a series of laboratory liquefaction tests (cyclic undrained triaxial testing) to clarify the area’s liquefaction characteristics using sand taken from a site in Urayasu City that experienced liquefaction.

Keywords: earthquake, liquefaction, Urayasu City, damage types, liquefaction strength, measure for liquefaction.

1 Introduction

The Great East Japan Earthquake ($M_w = 9.0$) occurred on March 11, 2011. Its epicentre was about 130 km away from the coast of Tohoku. Fig. 1 shows the seismic intensity observed in various parts of Japan. It illustrates that the earthquake was felt over much of Japan. Extensive damage was caused by the
huge tsunami (over 10 m high in some locations) triggered by the earthquake that struck the northeastern coastal areas near the epicentre. The number of dead or missing as of March 2013 is more than 18,500 people.

More than 400 km from the epicentre, the coastal areas around Tokyo Bay in the Kanto region, saw little damage from the tsunami, but there were many cases of soil liquefaction and settlement or tilting of buildings and the ground surface.

Figure 1: Epicentre and seismic intensity [1].

Fig. 2 and table 1 show that liquefaction damage in the Kanto area occurred not only around the Tokyo Bay coast, but also in coastal areas that had soft reclaimed soils along the Tone River, the Arakawa River and the Kasumigaura area that used to be covered by rivers, ponds or the sea. The most concentrated liquefaction damage occurred in Urayasu City, where about 8,700 houses were damaged.

Fig. 3(a) shows the acceleration-time history of the Great East Japan earthquake observed in Urayasu City near the city office. The seismic waves peaked at about 150 gal at maximum acceleration. This is not extremely large, but the duration of the seismic waves was more than 70 s, which was very long compared to past earthquakes. Urayasu City faces Tokyo Bay and about 75% of the city’s land has been reclaimed since the 1960s. The earthquake devastated this reclaimed area. For comparison, fig. 3(b) shows the acceleration-time history observed at the time of Great Hanshin-Awaji earthquake in Kobe City in 1995. The seismic waves of the Great Hanshin-Awaji earthquake have accelerations exceeding 400 gal for about 20 s, a relatively short time period. Liquefaction during the Great Hanshin-Awaji earthquake was limited to areas experiencing seismic intensities of greater than 6. In Urayasu City during the Great East Japan earthquake, however, liquefaction occurred not only in the Tokyo Bay coastal area but also in the coastal areas along the Tone, Arakawa and Kasumigaura areas which were formerly covered by rivers, ponds or the sea. In particular, Urayasu City, which faces Tokyo Bay and has about 75% of its land reclaimed since the 1960s, suffered severe liquefaction.
earthquake the seismic intensity was only $5^+$, so the long seismic wave duration appears to have contributed to the occurrence of liquefaction. In addition, three large aftershocks ($M_w = 7.0, 7.4, 7.2$) followed very quickly after the main quake, within about 20 to 35 min. This might also have contributed to the liquefaction.

Figure 2: Liquefied points in the Kanto area [2].

Table 1: Number of houses damaged by liquefaction [2].

<table>
<thead>
<tr>
<th>Name of city</th>
<th>Number of damaged houses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urayasu(Chiba)</td>
<td>8,700</td>
</tr>
<tr>
<td>Narashino(Chiba)</td>
<td>3,916</td>
</tr>
<tr>
<td>Itako(Ibaraki)</td>
<td>2,400</td>
</tr>
<tr>
<td>Katori(Chiba)</td>
<td>1,842</td>
</tr>
<tr>
<td>Kamisu(Ibaraki)</td>
<td>1,646</td>
</tr>
<tr>
<td>Chiba(Chiba)</td>
<td>1,043</td>
</tr>
<tr>
<td>Iwaki(Fukushima)</td>
<td>1,043</td>
</tr>
<tr>
<td>Funabashi(Chiba)</td>
<td>824</td>
</tr>
</tbody>
</table>

2 Characteristics of liquefaction damage in Urayasu City

Liquefaction damage in Urayasu City occurred throughout nearly all of the Nakamachi area, which was reclaimed after 1964, and all of the Shinmachi area, which was reclaimed after 1972. A summary of the most notable damage is as follows.
(1) Damage to small residences

Ground that lost its bearing capacity due to liquefaction could not support structures, resulting in settlement and tilting of small residences built on spread foundations. Sand eruptions caused by boiling effects were also found in many places (fig. 4).

(2) Damage to medium and large-scale buildings

Collective housing units and large-scale buildings in the area are on pile foundations, so they suffered relatively little damage. However, where the foundations contacted the ground, there were numerous instances of damaged utility lifelines such as drainpipes being disconnected (fig. 5).
(a) (b)

Figure 5:  (a) Foundation and ground contact point, (b) footing and ground contact point.

(3) Damage to other infrastructure features (roads and lifelines)
On roads, sand boiled from cracks in the pavement in many places. Also, manholes laid underground were lifted by buoyant forces, causing damage (fig. 6).

(a) (b)

Figure 6:  (a) Sand boiled onto a road, (b) lifted manhole.

3 Historical overview of Urayasu City’s terrain

Urayasu City lies in Chiba prefecture facing Tokyo Bay. The Edogawa River flows on its west side, where it borders Tokyo’s Edogawa Ward. It is located on Edogawa River Delta, and was a former fishing village.

After 1964, to allow for new housing, amusement parks and distribution bases for the steel industry, the area began to be landfilled. After 1980, when the landfilling was finished, the city covered four times more area than before. Figs. 7(a)–(d) [4] are aerial photographs showing the landfilled area in Urayasu from 1948 to the present.
Urayasu City can be divided into three parts, Motomachi, Nakamachi and Shinmachi, which mean Old Town, Middle Town and New Town in Japanese, respectively. Motomachi is inside the blue line in fig. 8. It lies on the Edogawa River Delta laid down by river deposits. It flourished as a fishing village in earlier times. Nakamachi is inside the yellow line in fig. 8. Reclamation there started in 1964. The newest area, Shinmachi, is inside the red line. It was reclaimed between 1972 and 1980, making it the newest land.

4 Methods of determining liquefaction potential

There are several methods used in Japan to determine liquefaction. The authors apply the FL and PL methods in this paper.
4.1 FL method

In foundation design in Japan, liquefaction is evaluated using a factor called the FL value that measures liquefaction resistance. It is calculated using

\[ FL = \frac{R}{L} \]  

(1)

where \( FL \) is the liquefaction resistance factor, \( R = c_W R_L \) the dynamic shear ratio, \( L \) the seismic shear stress ratio, \( R_L \) the cyclic triaxial shear stress ratio (over 20 cycles) and \( c_W \) a modification factor for earthquake ground motion.

![Figure 8: The three parts of Urayasu City: (Motomachi, Nakamachi and Shinmachi).](image)

Eqn (1) has been published by the Japan Road Association [5]. The FL value is calculated at 1 m depth increments and quantitatively evaluates the potential for liquefaction. If \( FL \) are lower than 1.0 at any depth, the ground is deemed to be subject to liquefaction.

4.2 PL method

Many local governments in Japan use the liquefaction index (PL value) as a tool for assessing liquefaction potential in earthquakes. For example, it can be used to make liquefaction hazard maps. The PL method [6] uses the previously described FL method and takes into consideration the depths and thicknesses of layers that are or are not susceptible to liquefaction. PL values can be obtained using

\[ PL = \int_0^{20} F_w(z)dz \]  

(2)

where \( F = 1 - FL \) for \( FL \leq 1.0 \) and \( F = 0 \) for \( FL > 1.0 \) and \( w(z) \) is a weight function for depth, given by \( w(z) = 10 - 0.5 z \). Using PL values, liquefaction potential can be assessed as shown in table 2.
Table 2: PL values and liquefaction possibility.

<table>
<thead>
<tr>
<th>PL value</th>
<th>Liquefaction possibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>quite low</td>
</tr>
<tr>
<td>0–5</td>
<td>low</td>
</tr>
<tr>
<td>5–15</td>
<td>high</td>
</tr>
<tr>
<td>15-</td>
<td>very high</td>
</tr>
</tbody>
</table>

5 Determination of soil liquefaction potential in Urayasu City

Figs. 9(a), (b) and (c) show the calculated FL values of three sites (Shinmachi, Nakamachi and Motomachi) in Urayasu City determined using published boring data [7]. The figures show data at Hinode in the Shinmachi area, Mihama in the Nakamachi area and Kitasakae in the Motomachi area, respectively. The PL values

Figure 9: Calculated FL values at (a) Hinode (Shinmachi), (b) Mihama (Nakamachi) and (c) Kitasakae (Motomachi).
of these sites, calculated using eqn (2), are shown in table 3. The calculated $FL$ values are lower than 1.0 at all depths at Hinode and Mihama, which are in the newly reclaimed land of Shinmachi and Nakamachi. In the area of the former fishing village of Kitasakae in Motomachi, some $FL$ values are higher than 1.0. That ground consists of silt deposits that are less prone to liquefaction. While the possibility of liquefaction at Hinode and Mihama is “very high” because of $PL$ values higher than 15, at Kitasakae the $PL$ value is lower than 15, and the liquefaction possibility as listed in table e is “high”.

### Table 3: Calculated PL value.

<table>
<thead>
<tr>
<th>Site</th>
<th>PL value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hinode (Shinmachi)</td>
<td>31.3</td>
</tr>
<tr>
<td>Mihama (Nakamachi)</td>
<td>31.3</td>
</tr>
<tr>
<td>Kitaei (Motomachi)</td>
<td>12.4</td>
</tr>
</tbody>
</table>

### 6 Liquefaction strength of Urayasu City sand

Using sand samples taken from Urayasu City, where much liquefaction occurred in the Great East Japan earthquake, a series of cyclic undrained triaxial tests were carried out. Toyoura standard sand was also tested for comparison.

The soil profiles and test conditions are shown in table 4 and table 5 and fig. 10, respectively. The difference between Urayasu sand and Toyoura sand is that Urayasu sand has more fine-grained material than Toyoura sand. Therefore, Urayasu sand’s maximum and minimum density are smaller than those of Toyoura sand.

### Table 4: Soil properties of sand tested.

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Urayasu</th>
<th>Toyoura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of soil particle $\rho_s$ (g/cm$^3$)</td>
<td>2.695</td>
<td>2.641</td>
</tr>
<tr>
<td>Maximum density $\rho_{\text{max}}$ (g/cm$^3$)</td>
<td>1.337</td>
<td>1.672</td>
</tr>
<tr>
<td>Minimum density $\rho_{\text{min}}$ (g/cm$^3$)</td>
<td>0.978</td>
<td>1.374</td>
</tr>
<tr>
<td>Mean particle size $D_{50}$ (mm)</td>
<td>0.148</td>
<td>0.161</td>
</tr>
<tr>
<td>Fine fraction content $F_C$ (%)</td>
<td>15.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### Table 5: Test conditions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$Dr$ (%)</th>
<th>$\sigma'_c$ (kPa)</th>
<th>$f$ (Hz)</th>
<th>$R$ $\sigma_d/(2\sigma'_c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyoura</td>
<td>40</td>
<td>100</td>
<td>0.2</td>
<td>0.12, 0.14, 0.16</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td></td>
<td>0.17, 0.19, 0.21</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td></td>
<td></td>
<td>0.21, 0.24, 0.29</td>
</tr>
<tr>
<td>Urayasu</td>
<td>60</td>
<td></td>
<td></td>
<td>0.17, 0.19, 0.21</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td></td>
<td></td>
<td>0.21, 0.24, 0.29</td>
</tr>
</tbody>
</table>
Fig. 11 shows the relationships between cyclic shear stress ratio and the number of loading repetitions for both sands. In Toyoura sand, differences in liquefaction intensity with changes in relative density are seen clearly. On the other hand, the liquefaction strength of Urayasu sand is not as affected by relative density. This is consistent with the results of Yokoyama et al. [7] as they varied the fine fraction content.

Fig. 12 plots the relationships between liquefaction strength and relative density for Urayasu and Toyoura sands. There is no difference with medium samples ($D_r = 60\%$), but in dense samples ($D_r = 80\%$), Urayasu sand tends to have a smaller liquefaction strength. This could be due to the fine fraction content as discussed above.

Figure 10: Sand particle sizes.

Figure 11: Relationship between cyclic stress ratio and number of cycles, (a) Toyoura sand, (b) Urayasu sand.
Figure 12: Relationship between liquefaction strength and relative density.

7 Measures against liquefaction in Urayasu City

Thick clay soil accumulates beneath the reclamation ground of Urayasu City as shown in fig. 9. It was concluded that the dewatering method was the most practical means of preventing a recurrence of liquefaction. However, consolidation settlement occurred in the demonstration experiment on site, which resulted in excluding it as a countermeasure method. The consolidation settlement in the lower layer of clay soil was caused by the increase of effective stress.

Another practical countermeasure method is the grid-form underground wall method, which is currently being considered for adoption. Its mechanism and merit are described below.

7.1 Mechanism and effect of the grid-form underground wall method

This method involves the supplication of a stabilizer, such as cement, in the ground and the development of underground walls in columnar shapes made with soft soil and the material stirred and mixed forcibly as shown in fig. 13. The walls are disposed in a lattice shape and surround liquefied ground, which restrains shearing deformation. Thus, liquefaction can be prevented. They can be constructed with low noise and vibration. Moreover, this method can be applied to both sand and clay.

Figure 13: The grid-form underground wall method [9].
7.2 Advantage of the method

To improve roads and housing land integrally, the governmental grant for Great East Japan Earthquake Reconstruction can be utilized. This is one of the greatest advantages.

![Figure 14: Mechanism of the grid-form underground wall method [9]: (a) without the wall, (b) with the wall.](image)

7.3 Study item about the method

Liquefaction prevention effect can be achieved by the improvement of the whole area. A consensus from all residents must be obtained when using the grid-form underground wall method. Therefore assemblies such as explanatory meetings are actively held at present.

8 Conclusions

1. In the Tohoku earthquake, even the Tokyo Bay coast, which is very far away from the epicentre, suffered devastating damage caused by liquefaction.
2. More than 70% of the ground in Urayasu City, which suffered the largest damage from liquefaction, was landfill area reclaimed after the 1960s.
3. $FL$ and $PL$ values calculated using current estimation methods indicate a high possibility of liquefaction.
4. A liquefaction resistance test on Urayasu sand revealed that it has less resistance to liquefaction despite the fact that it contains fine-grained fractions.
5. Liquefaction-resistant structures are used mainly for residential houses. Therefore, choosing inexpensive, economical liquefaction-resistant structures is very important. The grid-form underground wall method is one having the greatest advantages.
References