Study of the Mechanism of Liquefaction-induced Damage to Water Pipes during the Great East Japan Earthquake in Urayasu City

K. Ishikawa¹, S. Yasuda², S. Ikarashi³

ABSTRACT

Approximately 85% of Urayasu City was liquefied during the Great East Japan Earthquake, causing serious damage to water pipes. This shaking of liquefied ground (a type of sloshing) produced large cyclic compressive and tensile strains in water pipes in the horizontal plane near certain boundaries, resulting in the disconnection of water pipe joints. Two-dimensional seismic response analyses were conducted to demonstrate the concentration of horizontal tensile strain in five areas of Urayasu City under four levels of shear modulus by considering the effect of liquefaction. Analyzed results showed large tensile strain was induced on the ground surface where the bottom of the liquefaction layer was inclined. Large tensile strain was also induced on ground where shear modulus was low. These locations, where large tensile strain was induced, largely coincided with the sites where water pipes were damaged.

Introduction

The 2011 Great East Japan Earthquake, with a magnitude of Mw = 9.0, occurred in the Pacific Ocean about 130 km off the northeast coast of Japan’s main island on March 11, 2011. The epicentral distance was very long, about 380 to 400 km, and liquefaction occurred over a wide area of reclaimed land along Tokyo Bay. Large amounts of boiled sand, a large degree of settling, and a type of sloshing of the liquefied ground were observed in the Tokyo Bay area. According to Yasuda and Ishikawa (2012) and Towhata et al. (2012), many houses, roads, utilities, and river dikes were severely damaged by soil liquefaction. The most seriously damaged area was Urayasu City, where about 85% of the area was liquefied. Seismic intensities in the liquefied zones were not high, although the liquefied grounds were covered with boiled sand. Most likely, the very long duration of the main shock along with the large aftershock that hit 29 min later induced the severe liquefaction. Sidewalks and alleys buckled at several sites, probably due to the aforementioned sloshing of the liquefied ground. Water pipes were seriously damaged by the liquefaction. Disconnection of water pipe joints was found at many sites caused by the shaking of liquefied ground, i.e., a type of sloshing. The shaking produced large cyclic compressive and tensile strains in water pipes along the horizontal plane near some boundaries, resulting in the disconnection of pipe joints. The water pipe damage was a characteristic event not confirmed in previous earthquakes.

The authors recorded buckling damage on a flat road via field investigation after the earthquake. The buckling damage at the site in Maihama 3-chome is shown in Figure 1. The damage to the flat road is classified into two damage modes, as shown in Figure 2. In the first damage mode, some thrust might have occurred at the boundaries due to the sloshing of liquefied ground. In the

¹Keisuke Ishikawa, Tokyo Denki University, Assistant Professor, Saitama, Japan, ishikawa@g.dendai.ac.jp
²Susumu Yasuda, Tokyo Denki University, Professor, Saitama, Japan, yasuda@g.dendai.ac.jp
³Shota Ikarashi, Graduate School of Tokyo Denki University, Saitama, Japan
Fig. 1 Buckling damage to a flat road at the Maihama 3-chome study site

Fig. 2 Two possible mechanisms of heaving

Fig. 3 Water pipe damage and study site in Urayasu

Fig. 4 Aerial photograph of the study

second mode, horizontal buckling of the surface layer might have occurred due to the concentration of horizontal compressive stress. In this study, two-dimensional seismic response analyses were conducted to analyze the concentration of horizontal tensile strain at five areas in Urayasu City under four levels of shear modulus by considering the effect of liquefaction.

**Investigation of the Ground Status in the Study Area**

The study area is shown in Figure 3, and it includes the Urayasu City region. Urayasu consists of three areas: the Moto-machi area is the natural deposition ground and Naka-machi and Shin-machi are the reclaimed lands. Development of the area started in 1965. After the 2011 Great East Japan Earthquake, liquefaction was confirmed throughout the reclaimed lands but was not confirmed in Moto-machi. The present study considers five cross-sections with confirmed damage in the form of water leakage from affected water pipes following the earthquake. Ground
structure made the model using the surface wave exploration results, aerial photographs, and bathymetry results before reclamation.

Urayasu is located at the mouth of the Old Edo River. Therefore, the topography before reclamation was formed in the tidal flat, the old river channel, the sandbar, and the water route. The aerial photograph shown in Figure 4 was taken in 1961 (before reclamation) and shows these features. On the A-A’ line (Maihama 2-chome) shown in Figure 6, the sandbar in the river mouth of Old Edo River is confirmed; moreover, it is confirmed that there is a river channel near A’. On the B-B’ line (Maihama 3-chome), the Old Edo River channel is confirmed, and the sandbar (though not as clear as on the A-A’ line) is also confirmed. From this, the A-A’ line and B-B’ line show the topographical characteristics that cross the sandbar and the old river channel. However, the sandbar and water route of the river mouth on the C-C’ line (Tomioaka), D-D’ line (Imagawa), and E-E’ line (Irifune) could not be confirmed. Figure 5 shows the present sandbar location and water route of the Old Edo River; the locations of water pipe damage in the Maihama area are also shown. Water pipe damage was concentrated near the boundary of the river channel and the sandbar. Moreover, it is considered that the damage was concentrated near the point where the undersurface layer of the reclaimed land inclines.

The elevation of the ground before reclamation was confirmed with bathymetry, and the results are shown in Figure 6. On the A-A’ line, the elevation of the sandbar is high, and the elevation of the Old Edo River channel is about 2 to 3 m lower than the sandbar. Similarly, the B-B’ line confirms a difference of about 2 to 3 m in elevation between the river channel section and the sandbar section. The change in topography shown by aerial photography agreed with the change tendencies shown by numerical topography. In addition, the elevation of the C-C’, D-D’, and E-E’ lines, where the sandbar was not confirmed, was consistent. This suggests that there is almost no tilt in the undersurface of the reclaimed land in these cross-sections.

The objective of surface wave exploration is to understand the toughness of a ground surface (Ishikawa et al. 2014). These results are used to estimate the difference in the toughness of the
Fig. 7 Surface wave exploration result

ground from the construction boundaries of the ground surface. In this study, the exploration was conducted at a depth of 15 m and evaluated the distribution of the S-wave propagation velocity \( V_S \) of the surface lines. The surface wave exploration results of each of the lines are shown in Figure 7. The results confirm that the loose ground has deposited on the A-A’ line at 60–100 m; this layer is the ground that was reclaimed from the old river channel. The B-B’ line has comparatively tough ground at 30–70 m and comparatively loose ground at 0–30 m and 100–150 m. Thus, the topographical characteristics of the sandbar and the river channel are distinguishable from the exploration results. The C-C’ line has comparatively tough ground at 0–10 m. A metropolitan expressway and a trunk road pass along this line near 0 m, and so, the ground toughness is affected by the consequent improvement in surface ground soil compaction. In a residential street, i.e., after a distance of 20 m on the C-C’ line, loose ground has deposited thickly; \( V_S \) is about 100 m/s. The D-D’ line has comparatively tough ground at 0–20 m. Here, the toughness of the ground may be influenced by the construction of a medium-rise structure and its pile foundation. After a distance of 20 m, a low-speed degree band was confirmed in the residential street, i.e., as observed on the C-C’ line. Compared with the other results, the E-E’ line does not have a characteristic layer structure. However, it was confirmed that both loose and tough ground were distributed sparsely.

**Ground modeling of a verification section**

To reproduce the ground structure in detail, a ground model was constructed according to the following procedures:
1) The basic analysis model is the layer structure in each 250 × 250 m mesh created in the representative soil profile model (RSPM). The details of the method for constructing the RSPM are given in JGS (2014).

2) As for the A-A' and B-B' lines, the sandbar and the old river channel were confirmed; this model corrects the basic analysis model in terms of the inclination of the undersurface of the reclamation layer based on the bathymetry.

3) The analysis area is the reclaimed land of the Tokyo Bay coast. Consolidation of the alluvial clay layer was confirmed by the overburden load of banking and the reclamation ground (Chiba Prefecture, 2014). The depth of the layer at the lower end of the reclamation ground was corrected by evaluating the amount of consolidation of the alluvial clay layer according to the layer thickness of the banking and reclaimed ground.

4) The surface of the analysis model evaluated was based on the $V_S$ value from surface wave exploration. After considering the measurement accuracy of the exploration results, the depth direction was assumed at 15 m. The $V_S$ values were categorized into four groups: very loose layer, 60 m/s; loose layer, 100 m/s; slightly loose layer, 140 m/s; and middle rank layer, 200 m/s.

The analysis model is shown in Figure 8. Hatching shows the reclaimed land that is considered to have liquefied. In the ground model of the A-A' line, the undersurface of the reclamation layer inclines, and the boundary of this topography is near 70 m. In the ground model of the B-B' line, the loose layer that buried the old river channel is confirmed at 0–30 m, and the undersurface of the reclamation layer gently rises. A loose layer with a slow S-wave propagation velocity occurs near the model center. In the ground model of the C-C' and D-D' lines, the area with high $V_S$ values near 0 m is influenced by the boundary of a structure. The residential street after 20 m has

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**Fig. 8 Created analysis model**

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small $V_s$ values and is a loose layer. In the ground model of the E-E’ line, the reclamation layer with a rapid band is sparsely distributed.

**Seismic Response Analysis Considering the Effect of Liquefaction**

*Various Conditions of Seismic Response Analysis*

This analysis assumed the existence or nonexistence of liquefaction of a reclaimed land layer. The analysis method used in this study is “FLUSH,” a two-dimensional FEM seismic response analysis. Evaluation of the shear modulus affected by the liquefaction was accomplished using two methods. The first method assumed that the reclaimed land layer did not liquefy, and the shear modulus was calculated using the equivalent liner method. The second method assumed that the reclaimed land layer did liquefy. On the ground that liquefied, a very large shear strain occurs in response to the action of a small shear stress. According to Yasuda et al. (2004), the shear modulus of the liquefaction ground becomes a very small value, and so, the following rates were used to evaluate the coefficient of the shear modulus of an infinitesimal strain. The rates were set to $1/50$, $1/100$, and $1/200$, and the model is linear. In the animation of this earthquake, it was confirmed that the ground liquefied by a cycle of about $4$ s was shaking. The S-wave propagation velocity of the liquefied ground is set to $6$ m/s when the layer thickness of the liquefaction layer is $8$ m. The shear modulus $V_s$ value is approximately $100$ kPa, and examined this value. The shear modulus of the liquefaction layer was analyzed for its accordance with five potential patterns.

The setup of the shear modulus for a layer shallower than the alluvial sand layer was established from the $V_s$ value acquired by surface wave exploration. The layer deeper than the alluvial clay layer was set up using an average of the $N$ value from the RSPM ground model. The dynamic deformation properties follow Yasuda and Yamaguchi (1985). The unit weight of each layer is a general value. As a boundary condition, a lateral boundary is taken as an energy transfer boundary, and the bottom as a rigid basement. The groundwater level is a water level established by the RSPM. Input earthquake motion is based on observation records from the Yumenoshima Observatory of the Bureau of Port and Harbor, Tokyo Metropolitan Government. The seismic waves are shown in earthquake engineering observation records of seismic bedrock. The time history of input earthquake motion is shown in Figure 9.

![Fig. 9 Time history of input earthquake motion](image-url)
Results of Seismic Response Analysis

As an example of an analysis result, the maximum acceleration contour figure and deformation figure of line A-A' are shown in Figure 10. To represent the most extreme condition, the shear modulus of the liquefaction layer is reduced to 1/200 of the initial shear modulus. The maximum input earthquake motion is approximately 0.6 m/s². Maximum acceleration is a response of about 2 m/s² near the ground surface. It was confirmed that maximum acceleration is amplified close to where the liquefaction layer inclines. The acceleration response of other sections showed the same tendency. Deformation occurs after maximum acceleration. It was confirmed that relative displacement of the ground occurred close to where the undersurface of the liquefaction layer inclines. The horizontal relative displacement by sloshing of a liquefaction layer is 0.1–0.2 m.

The surface wave exploration and analysis results for each section are shown in Figure 11. The analysis results show the maximum tensile strain at 1.5 m, i.e., the construction depth of water pipes. On the A-A' line, the largest tensile strain occurred near 60 m where the undersurface of the reclamration layer inclines. At the location of large tensile strain, $V_S$ values are low compared with those of the surrounding ground. Therefore, a decline in the shear modulus of a liquefaction layer becomes a factor that increases tensile strain. When the shear modulus of a liquefaction layer was set to 100 kPa, it was confirmed that tensile strain increase by about 1.5%. Water pipe damage was confirmed where tensile strain is amplified. On the B-B' line near the old channel of the Old Edo river at 0 m, the topography changes to a sandbar from 30 m. Therefore, the undersurface of the reclaimed layer gently rises from 30 m. Large tensile strain is generated where the $V_S$ value is small compared with that of the surrounding ground. Tougher ground is located near 50 m, and it is considered that the tensile strain was concentrated on the loose ground because the tougher ground and loose ground collide. On the C-C' line, water pipe damage was concentrated around 70–80 m, and the tensile strain in this region is about 1.0%. A trunk road and the boundary of a residential street are found at around 20 m, and tensile strain from this boundary is confirmed. Due to the shaking, the residential section that liquefied is considered to have repeatedly collided with the trunk road of the nonliquefied ground. This is a structural boundary (as shown by the differing shear modulus of the ground), and this constrained the damage caused by the shaking of the liquefied ground.

From the above findings, the strain in the ground where the entire region liquefied can be considered to have been caused by one of the two factors. The first factor, i.e., the liquefaction of the ground, confirms that strain is concentrated near topographical or structural boundaries. The second factor, i.e., the reclamration layer and heterogeneous ground, confirms that strain occurs in the case of an earthquake where there are differences in the shear modulus of the ground.
Moreover, when the groundwater level is deep, the tensile strain generated at the construction depth of water pipes is small.

Conclusions

The following knowledge was acquired from the two-dimensional seismic response analysis of water pipe damage due to liquefaction in the study area in Urayasu City.
1) When the ground liquefied across the entire region, the strain caused by earthquake-induced shaking occurred near topographical and structural boundaries where the undersurface of the liquefaction layer inclined.
2) A reclamation layer of heterogeneous ground will experience increased strain and shaking after the liquefaction of areas that have shear differences in the inclined liquefaction layer.
3) Water pipe damage occurred where tensile strain was generated in connection with the shaking of liquefied ground. Moreover, it appears that ground shaking is related to the disconnection of water pipe joints.

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