LIQUEFACTION-INDUCED DAMAGE TO WOODEN HOUSES IN HIROSHIMA AND TOKYO DURING FUTURE EARTHQUAKES

Susumu YASUDA¹, Keisuke ISHIKAWA²

ABSTRACT

Hazard maps for liquefaction-induced damage to wooden houses during future supposed earthquakes in Hiroshima City and the Kita-Senju area of Tokyo were estimated. Representative soil profile models in a mesh size of 250 m × 250 m in plan constructed by the Japanese Geotechnical Society were used to estimate the liquefaction strength ratio (CSR). The cyclic shear stress ratio (CSS) was evaluated by seismic response analysis. The damage to wooden houses was evaluated based on a new method proposed by the MLIT of Japan that combines the liquefaction potential, PL, and the thickness of the non-liquefied layer, H₁. It is estimated that liquefaction-induced damage would occur in many meshes during future earthquakes in both Hiroshima City and the Kita-Senju area. Hazard maps estimated by PL only and by PL and H₁ coincide for the Kita-Senju area but differ for Hiroshima City because of the effect of the depth of the water table.

Keywords: Liquefaction; Soil profile model; Seismic zoning, Seismic response analysis, Cyclic torsional shear test

1. INTRODUCTION

The Great East Japan (Tohoku) 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, as illustrated in Figure 1. Soil liquefaction occurred in a very wide area from the Tohoku region to the Kanto region, including the Tokyo Metropolitan Area, because the earthquake was huge (Yasuda et al., 2012).

![Figure 1. Map of rupture planes caused by the 2011 Great East Japan (Tohoku) Earthquake and a future Nankai Earthquake in Japan](image)

In Japan, a similar huge earthquake is predicted to occur in the near future along the Nankai Trough in

¹Professor, Tokyo Denki University, Hiki-gun, Saitama, Japan, yasuda@g.dendai.ac.jp
²Assistant Professor, Tokyo Denki University, Hiki-gun, Saitama, Japan, Ishikawa@g.dendai.ac.jp
the Pacific Ocean, causing liquefaction in a wide area. Liquefaction occurred in Hiroshima City during the 1946 Nankai Earthquake ($M_j=8.0$), though its epicenter was very far from the city. Another worry is a strong earthquake occurring in the Tokyo Metropolitan Area. Seismic zoning for liquefaction-induced damage to wooden houses in Hiroshima City and the Kita-Senju area of Tokyo were carried out based on representative soil profile models (RSPMs) and seismic response analyses. In Japan, the construction of RSPMs started in 2007 by using a newly developed system (Yasuda et al., 2010), and RSPMs have been prepared for 34 cities, including Tokyo and Hiroshima. These RSPMs are available on the website of the Japanese Geotechnical Society. In this system, RSPMs of 250 m × 250 m in plan are constructed based on soil boring data. The procedure to construct an RSPM is as follows:

1. Select a mesh to construct the model. A standard 250 m mesh map published by the Geographic Survey Institute of Japan is used.
2. Place digital boring data in the mesh. If necessary, place boring data in the neighbor meshes as well. Inappropriate data are deleted by considering topography and geology. The depth of bedrock in each boring is estimated for engineering purposes.
3. The system automatically constructs the RSPM to the depth of bedrock by averaging soil type, SPT $N$-value, and groundwater level.

In default, the soil type choices are: gravel soil, sandy soil, clayey soil, organic soil, volcanic clay, peat, artificial material and rock, but minor modifications of these types are available.

2. ESTIMATION OF LIQUEFACTION-INDUCED DAMAGE TO WOODEN HOUSES IN HIROSHIMA CITY

2.1 Future earthquakes supposed to occur along the Nankai Trough in Japan

In and around Japan, four tectonic plates are in intimate contact, as shown in Figure 1. The large Eurasian Plate lies along and through west Japan, and the North American Plate lies through the northeastern part of the country. From the east of Japan, the Pacific Plate approaches the country at a rate of about 10 cm per year, and from the south, the Philippine Sea Plate approaches at a rate of about 5 cm per year. The Pacific Plate collides with, and is depressed by, the North American Plate, forming the Japanese Trench, about 8000 m deep, off the Tohoku region and the Kanto region. The rupture plane caused by the 2011 Great East Japan (Tohoku) Earthquake, with a magnitude of $M_w=9.0$, occurred along the Japanese Trench and caused liquefaction in a very wide area from the Tohoku region to the Kanto region. The Philippine Sea Plate collides with, and is depressed by, the Eurasian Plate, forming the Nankai Trough off the Kyushu region, the Nankai region and the Tokai region. Huge earthquakes have occurred along the Nankai Trough at intervals of about 90 to 150 years. Liquefaction occurred in Hiroshima City during the 1946 Nankai Earthquake ($M_j=8.0$), though its epicenter was very far from the city. Thus, there is concern that another huge earthquake could occur in the near future along the Nankai Trough and cause liquefaction in a wide area, including Hiroshima City.

2.2 Topographical and geological conditions in Hiroshima City

Figure 2 shows a map of Hiroshima City and its environs. The south side of the city faces Hiroshima Bay, and other sides are surrounded by hills of 300 to 700 m in height. A fairly big river, the Ohta River, runs from the mountainous area to the north of the city to form a natural delta into the bay. This delta has been artificially landfilled and enlarged from the seventeenth century, as shown in Figure 3. Now, several hundred thousand people live on the delta and filled land. For Hiroshima City, RSPMs were constructed by Tsuchida et al. for an area of approximately 10 km × 5 km containing the natural delta and filled land, as shown in Figure 4. Figure 5 shows a series of RSPMs from upstream to downstream of the Ohta River along the A-A′ line in Figure 4. A loose sand layer with SPT $N$-value of 5 to 10 is deposited from the ground surface to several meters in the whole area. A comparatively dense sand layer is deposit under the loose sand layer in the north (upstream) zone, and a soft clayey layer is deposited under the loose sand layer in the south (downstream) zone. The water table is 3 to 5 m deep in the upstream zone and rises to a depth of 1 to 2 m in the southern part of the city.
Figure 2. Topographical and geological conditions in Hiroshima City

Figure 3. History of reclamation and liquefied sites during past earthquakes

Figure 4. Area where RSPMs were constructed and distribution of estimated peak surface acceleration in Hiroshima City

2.3 Method for estimating liquefaction

Figure 6 summarizes the factors used to estimate the liquefaction potential of a soil profile model. The liquefaction strength ratio (CSR), $R$, was estimated from the SPT $N$-value and the fines content, $F_C$. The cyclic shear stress ratio (CSS), $L$, was evaluated by seismic response analysis. The safety factor against liquefaction, $F_L$, was calculated as $F_L = R/L$. One-dimensional seismic response analysis was
carried out using the “DYNEQ” computer program to estimate $L$. In the analyses, the shear wave velocity, $V_s$, was estimated from SPT $N$-values by the relationship introduced in the Specification of Highway Bridges in Japan (JRA, 2012). The shear wave velocity of bedrock was assumed as 350m/s. Figure 7 shows a graph of the input seismic wave predicted by the Japanese Cabinet Office. This wave is supposed to be induced at Hiroshima City Hall during a future huge earthquake along the Nankai Trough. The peak acceleration of the input motion is 147.8 gals. Figures 4 and 8 show the distribution of the calculated peak surface acceleration, $A_{s,max}$, in the studied area and along the A-A’ line, respectively. $A_{s,max}$ in the north is 200 to 300 gals, but it declines to 150 to 200 gals in the south. Figure 9 shows soil profiles, assumed $V_s$ and calculated $A_{s,max}$ by depth at two typical sites in the north and south zones. As shown in this figure, $A_{s,max}$ in the south is smaller than in the north because a soft clay layer is deposited between the bedrock and the loose sandy layer in the south.

![Image of soil profile models along A-A’ line in Hiroshima City](image)

Figure 5. Soil profile models along A-A’ line in Hiroshima City

![Image of factors used to estimate the safety factor against liquefaction](image)

Figure 6. Factors used to estimate the safety factor against liquefaction
The liquefaction strength, $R$, was evaluated by the formulae used in the Specification of Highway Bridges in Japan. However the effect of the duration of the seismic wave was considered in the correction factor, $C_2$, which is defined in Figure 10, because the duration of the shaking is long, about 1 minute, though the maximum input acceleration is not large, 147.8 gals. So, the authors conducted cyclic torsional shear tests using the seismic wave shown in Figure 7. In the current seismic design code for highway bridges in Japan, the correction factor for normal seismic waves is assumed to be around 1.5. However, the test results showed $C_2$ must be 1.2 for this seismic wave.
Figure 10. Correction factor, $C_2$, to consider the effect of long duration on the estimation of liquefaction potential

2.4 Methods for evaluating liquefaction-induced damage to structures

The severity of liquefaction at a site cannot be evaluated by $F_L$ values only. A parameter called liquefaction potential, $P_L$, defined in Figure 11, was proposed by Tatsuoka et al. (Iwasaki et al. in 1978, Tatsuoka et al. in 1980). In Japan, $P_L$ has been widely used for hazard maps to present general damage due to liquefaction. However, it has not been clear whether the potential damage to wooden houses can be estimated by $P_L$ only. According to case studies of the effect of the water table on the damage to houses during past earthquakes, the depth of the ground water table was an important factor to control the penetration settlement and inclination of houses (Yasuda and Hashimoto, 2016). For example, the authors and their colleague measured the depth of the water table at the sites of about 28 houses damaged due to liquefaction during the 2011 Great East Japan Earthquake in the Irifune and Mihama districts of Urayasu City. The measured depths are classified by the level of damage to wooden houses and plotted in Figure 12. As shown in this figure, a water table of about 1.7 to 2.0 m below the ground surface was the critical depth to prevent damage to houses (Ishikawa et al., 2014).

Figure 11. Evaluation of likely damage to structures based on liquefaction potential, $P_L$.
Similar studies on the effect of the depth of the water table or the thickness of the unliquefied surface layer, $H_1$, were conducted in several cities damaged by the 2011 Great East Japan Earthquake. If the surface sand layer is loose and liquefiable in saturated condition, $H_1$ is the same as the depth of the water table. Based on these studies, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) proposed a new criterion to estimate the liquefaction-induced damage to wooden houses in 2014. Figure 13 shows the ground classifications based on this new criterion, in which the possibility of damage can be estimated by liquefaction potential, $P_L$, and the thickness, $H_1$, of the non-liquefied layer overlaying the liquefied layer. In this relationship, 3 m is defined as the critical thickness of $H_1$ to prevent damage to wooden houses.

In this paper, the hazard maps were evaluated by two methods, the $P_L$ value only and the new criterion combining $P_L$ and $H_1$. Figure 13. A new method to estimate the liquefaction-induced damage to wooden houses proposed in 2014 by MLIT

Figure 14 explains the reason why about 3 m must be the critical depth to cause liquefaction-induced damage to wooden houses. For the non-liquefied layer above the water table, the water table increases during shaking for two reasons: i) the inflow of water from the lower liquefied layer due to liquefaction-induced densification, and ii) the spewing out of water due to excess pore water pressure induced in the liquefied layer. The inflow of water from the lower liquefied layer increases the water level by 1 m or less if the thickness and the volumetric strain of the liquefied layer are several meters and about 5%, respectively. The water spewed out from the liquefied layer occasionally reaches a few meters above the ground surface, but it flows through narrow spaces, such as cracks in the ground, and lasts only for a short time. Therefore, the ground water level usually increases by only a meter or so. Considering this increase in the water table due to liquefaction, a water table of about 3 m below the ground surface must be the critical depth to prevent damage to a house (Yasuda and Hashimoto, 2016).

Figure 14. Diagram of the critical depth of a water table to prevent the liquefaction-induced settlement and tilting of a house.
2.5 Estimated liquefaction-induced damage in Hiroshima City

Figures 15 (1), (2) show hazard maps for damage to general structures in Hiroshima City based on $P_L$ and for liquefaction-induced damage to wooden houses in Hiroshima City based on $P_L$ and $H_1$, respectively. The estimated $P_L$ in the north zone is larger than that in the south zone because the loose sandy layer is thick in the north zone. However, the distribution of estimated damage to wooden houses is the opposite. In the north zone, severe damage to wooden houses is not predicted because the ground water table is deeper than 3 m in many meshes. So, the depth of the water table must be carefully considered in the preparation of a hazard map for liquefaction-induced damage to wooden houses.

Figure 15. Hazard map for damage to general structures and wooden houses in Hiroshima City

3. ESTIMATION OF LIQUEFACTION-INDUCED DAMAGE TO WOODEN HOUSES IN THE KITA-SENJU AREA OF TOKYO

3.1 Estimated future earthquakes in Tokyo

Many earthquakes have occurred in and around Tokyo due to complicated movements of the Pacific Plate, the Philippine Sea Plate, and the North American Plate. Big subduction-zone offshore earthquakes have occurred between the Pacific Plate and the North American Plate in the east and between the Philippine Sea Plate and North American Plate in the south. Inland earthquakes have occurred at the boundaries of three plates or in these plates. As it is not easy to predict the type of earthquake that could hit Tokyo in the near future, the potential damage due to several types of earthquake has been estimated by the Tokyo Metropolitan Government. The damage due to a possible inland earthquake at the boundary between the Philippine Sea Plate and the North American Plate would adversely affect the Kita-Senju area of Tokyo. Thus, the likely liquefaction-induced damage to wooden houses in this area was evaluated.

3.2 Topographical and geological condition in the Kita-Senju area of Tokyo

The Kita-Senju area of Adachi-ku, Tokyo is a small area of about 4 km × 3 km surrounded by the Arakawa and the Sumida rivers as shown in Figure 16. This area is an alluvial lowland formed by sedimentation from rivers. Before the twentieth century, this area was mainly used as rice fields. In the early twentieth century, residential and commercial districts were developed in this area. A big river, the Old Sumida River, flowed through the Yanagihara district and many moats were formed. This river and the moats were filled by the 1923 Kanto Earthquake. During the Kanto Earthquake, various damages occurred in the Kita-Senju area. Cracks and sand boils due to liquefaction occurred in the Yanagihara district along the Old Sumida River, resulting in damage to houses and irrigation canals,
as shown in Figure 16. A rail of the Tobu Line was suspended above the ground surface due to the settlement of an embankment. Now, about 70,000 people live in the Kita-Senju area. Moreover, about 1.5 million people pass through Kita-Senju Station each day because six railways are connected at the station. This concentration of passengers makes the station the sixth busiest in the world. Figure 17 shows wooden houses at Yanagihara district. For Tokyo, RSPMs were constructed within a wide area of approximately 20km × 20km. Figure 18 shows a series of RSPMs along the A-A’ line from the northwest to the southeast in the Kita-Senju area. As can be seen in the models, an alluvial sandy or gravelly soil layer is deposited from the ground surface to a depth of about 3 to 15 m. The sandy layer is thick and dense at and around Kita-Senju Station. However, the sandy layer is thin and loose to the west and east of the station zone. A soft alluvial clay layer is deposited under the sandy layer to a depth of about 20 to 30 m.

Figure 16. Current map and liquefaction-associated damage during the 1923 Kanto Earthquake in Kita-senju area of Tokyo

Figure 17. Wooden houses at Yanagihara district
3.3 Estimated liquefaction-induced damage in the Kita-Senju area

The methods used to estimate liquefaction potential and liquefaction-induced damage to wooden houses in the Kita-Senju district were almost same as those applied to estimate these factors in Hiroshima City except the estimation method for the liquefaction strength ratio, $R$. The method developed by the author et al. (Yasuda et al. 2004) was applied to estimate $R$, because this method is better than the JRA method in Tokyo. Figure 19 shows a graph of the input seismic wave predicted by the Japanese Cabinet Office. This wave is expected to be induced in the Kita-Senju area during a future inland earthquake resulting from a collision between the Philippine Sea Plate and the North American Plate. The peak acceleration of the input motion is 243.1 gals. The calculated peak surface acceleration, $A_{\text{max}}$, is about 250 to 450 gals, as shown in Figures 20. The upper part of Figure 17 shows the distribution of peak surface acceleration along the A-A’ line. The peak surface acceleration near Kita-Senju Station is lower than that in the zone surrounding the station due to the surface dense sandy layer.
Figure 20. Area where RSPMs were constructed and distribution of estimated peak surface acceleration in Kita-Senju area.

Figures 21 (1), (2) show the hazard maps for damage to general structures in the Kita-Senju area based on $P_L$ and for liquefaction-induced damage to wooden houses in the area based on $P_L$ and $H_1$, respectively. $P_L$ is greater than 5 in about half of all meshes and exceeds 15 in 5 meshes. However, $P_L$ is less than 5 at and around Kita-Senju Station because the surface sandy layer is dense, as mentioned before. Meshes evaluated as rank C in Figure 21 (2) mostly coincide with the meshes where $P_L$ is greater than 5 in Figure 21 (1). So, the two kinds of hazard map coincide fairly well for the Kita-Senju area, because the ground water table in the area is shallower than 3 m. In Japan, industry developed rapidly from the beginning of twentieth century. Due to a lack of water, many wells were excavated and the ground water was drawn down in the lowland of Tokyo. This extraction caused subsidence due to the consolidation of the soft clay layer. Subsidence reached a maximum value in about 1970, then stopped because the extraction of ground water was prohibited. About 124 km$^2$ of the area of Tokyo is below sea level (Yasuda, 2009). In the Kita-Senju area, the ground level elevation is about zero, and the ground water table is shallow, about GL-1 m to -2m.

Figure 21. Hazard map for damage to general structures and wooden houses in in the Kita-Senju area in Tokyo.
4. CONCLUSIONS

Hazard maps of liquefaction-induced damage to wooden houses in Hiroshima City and the Kita-Senju area of Tokyo were estimated based on representative soil profile models and seismic response analyses. The following conclusions were derived through the studies:

(1) Damage to wooden houses due to liquefaction must be evaluated not only from liquefaction potential, $P_L$, but also from the thickness of the non-liquefied surface layer, $H_1$, as newly proposed by the MLIT of Japan.

(2) Representative soil profile models of 250 m × 250 m in plan are useful as a database to make hazard maps of liquefaction-induced damage.

(3) In Hiroshima City, liquefaction-induced damage would probably occur in many meshes during a huge earthquake that might occur in the future along the Nankai Trough, even though its epicenter was very far from the city. However, two hazard maps, one estimated by $P_L$ only, and the other based on $P_L$ and $H_1$, differ because of the effect of the ground water table. So, the depth of the water table must be carefully considered in preparing a hazard map for liquefaction-induced damage to wooden houses.

(4) In the Kita-Senju area of Tokyo, liquefaction-induced damage would also probably be induced by a future inland earthquake. Hazard maps for this area estimated by $P_L$ only and by $P_L$ and $H_1$ coincide because the water table is shallow in the area.

5. ACKNOWLEDGMENTS

This work was supported by Council for Science, Technology and Innovation(CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), “Enhancement of societal resiliency against natural disasters”(Funding agency: JST). Several graduate students at Tokyo Denki University assisted in the analyses. The authors express their sincere appreciation.

6. REFERENCES


Yasuda S and Hashimoto T (2016). New project to prevent liquefaction-induced damage in a wide existing residential area by lowering the ground water table. Soil Dynamics and Earthquake Engineering, 91, pp 246–259.