Development of Probabilistic Liquefaction Hazard Maps by Ground Settlement



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SUMMARY:

Physical damage to structures due to liquefaction is mainly caused by ground settlement. Thus, the liquefaction hazard indicated by ground settlement is a more direct way to recognize the linkage between structural damage and the potential liquefaction hazard. Conventional liquefaction hazard maps use color coding to indicate the degree of hazard, which is based on the classified liquefaction potential. This measure is difficult for ordinary residents to understand because it is not a quantitative expression. In this study, a probabilistic liquefaction hazard analysis based on the settlement of the ground surface is developed. In order to confirm the validity of the proposed method, exceedance probability curves and probabilistic hazard maps of the Tokyo metropolitan area have been created.

Keywords: liquefaction, probabilistic hazard analysis, hazard map, ground settlement

1. INTRODUCTION

Conventional liquefaction hazard maps use color coding to indicate the degree of hazard, which is calculated from the liquefaction potential (PL value) based on earthquake scenarios in the target map area. These maps are difficult for ordinary residents to understand. While the maps make people aware of the possibility of a liquefaction hazard, they are not conducive to the development of practical countermeasures since quantitative expressions of the hazards are not provided. Structural damage due to liquefaction is primarily caused by ground settlement. Thus, measuring the liquefaction hazard based on ground settlement is a more direct way to recognize the linkage between structural damage and the liquefaction hazard.

In this study, we have attempted to conduct a probabilistic evaluation using ground surface settlement as the index. Our fundamental approach was to calculate how much a particular location would settle, and with what probability, based on the location, magnitude, and probability of occurrence of all possible earthquakes. We then attempted to develop a probabilistic liquefaction hazard map using the proposed method.

2. METHODOLOGY

The 2011 East Japan Earthquake (Mw 9.0) caused a lot of liquefaction damage mainly in the Tokyo Bay area. Most damage to houses, lifelines, and the infrastructure was caused by ground settlement. The basic approach to probabilistic liquefaction hazard analysis (PLHA) applies the method proposed by Cornell (1968) and used by the Headquarters for Earthquake Research Promotion to prepare National Hazard Maps for Japan (National Research Institute for Earth Science and Disaster Prevention, 2002), that is, the probabilistic seismic hazard analysis (PSHA) method, to liquefaction. In this case, seismic intensity is being replaced with the level of liquefaction as the hazard being examined.



Figure 2.1. Flow of a probabilistic liquefaction hazard analysis focused on ground settlement

Conventional liquefaction hazard maps indicate the degree of hazard with such classifications as "Large," "Medium," and "Small" based on the liquefaction potential (PL value). This is a qualitative indication. The proposed method is distinctive in its use of liquefaction-induced ground surface settlement as the index for measuring the liquefaction hazard.

The flow of a probabilistic liquefaction hazard analysis focused on ground settlement is shown in Figure 2.1. The methods of calculating the liquefaction-induced ground settlement at one site, due to the occurrence of a particular earthquake, are as follows. First, we obtain the peak ground acceleration on the engineering base layer at the target site using the existing attenuation relations. From that, we calculate the peak ground acceleration at the ground surface as a function of the amplification ratio of subsurface layers. Next, we calculate the factor of safety against liquefaction (FL value) of each layer using the methods in the Specification for Highway Bridges (Japan Road Association ed., 2002). At this point we find the settlement of the ground surface using the relationship between the FL value and the post-liquefaction volumetric strain, as proposed by Ishihara and Yoshimi (1992). This important relationship is illustrated in Figure 2.2. Here, D_r and γ_{max} refer to the relative density and the maximum shear strain. We assume that the ground is horizontally-layered in the conversion from the volumetric strain of each layer through the depth of sand deposit to the settlement of the ground surface. We perform this operation for all earthquakes around the target site, considering the seismic activity and variation of parameters which characterize those earthquakes, and then combine the results above with annual exceedance probabilities of ground surface settlement to create the probabilistic hazard curves of liquefaction-induced ground settlement.



Figure 2.2. Diagram showing the volumetric strain as a function of the factor of safety (Ishihara and Yoshimine, 1992)

3. RESULTS

The probabilistic liquefaction hazard curves of specific sites and the probabilistic liquefaction hazard map of the Tokyo metropolitan area are proposed to verify the validity of the proposed method.

3.1. Probabilistic Liquefaction Hazard Curves

As an example, we tried to find the probabilistic liquefaction hazard curve for typical sandy ground in the Tokyo metropolitan area. The sites studied are shown in **Figure 3.1**. The soil properties of each site are listed in **Table 3.1**. This is the data from the Report on Envisioned Damage Due to an Epicentral Earthquake in Tokyo (Tokyo Metropolitan Government, 1997). In addition, the groundwater levels of all sites were set at one meter below ground, to maintain consistency with the report.

The attenuation relationship for peak ground acceleration proposed by Shi and Midorikawa (1999) was employed to estimate the peak ground acceleration on the engineering base layers, since it offers an estimation formula that differs by earthquake type (crustal earthquake, inter-plate earthquake, and inner-plate earthquake), and to ensure consistency with the fact that liquefaction judgments in the Specification for Highway Bridges are made by earthquake type (i.e., Type I; inter-plate earthquake, Type II; inland earthquake).

The dataset of the seismic activity model used by the Japan Seismic Hazard Information Station (J-SHIS, which is managed by the National Research Institute for Earth Science and Disaster Prevention) has been used in this analysis.



Figure 3.1. Sites studied

Table 3.1. Soil properties of sites studied (1) Site A

Layer	Thickness	Soil tripo	γt2	γt1	D50	FC	SPT	
number	(m)	Son type	(kN/m^3)	(kN/m^3)	(mm)	(%)	N value	
1	6.0	alluvial clay	14.7150	12.7530	0.040	65.0	1	
2	14.0	alluvial sand	16.6770	14.7150	0.350	10.0	5	
3	15.0	alluvial clay	15.6960	13.7340	0.040	65.0	5	
4	15.0	diluvial sand	18.1485	16.1865	0.350	10.0	30	
5	-	Edogawa layer	20.6010	-	-	-	above 50	

(2) Site B

Layer	Thickness	Soil type	γt2	γt1	D50	FC	SPT
number	(m)		(kN/m^3)	(kN/m^3)	(mm)	(%)	N value
1	5.0	alluvial sand	16.6770	14.7150	0.350	10.0	5
2	15.0	alluvial gravel	19.6200	17.6580	2.000	0.0	30
3	-	equivalent Kazusa layer	19.6200	-	-	-	above 50

(3) Site C

Layer number	Thickness (m)	Soil type	γt2 (kN/m ³)	γt1 (kN/m ³)	D50 (mm)	FC (%)	SPT N value
1	4.0	alluvial clay	14.7150	12.7530	0.040	65.0	1
2	4.0	alluvial sand	18.6390	16.6770	0.350	10.0	40
3	7.0	alluvial clay	14.7150	12.7530	0.040	65.0	1
4	5.0	alluvial sand	17.6580	15.6960	0.350	10.0	20
5	10.0	alluvial clay	15.6960	13.7340	0.040	65.0	5
6	5.0	diluvial gravel	19.6200	17.6580	2.000	0.0	50
7	-	Edogawa layer	20.6010	-	-	-	above 50

Note: γ t1: volume density above groundwater level, γ t2: volume density below groundwater level, D50: mean particle diameter

FC: fine fraction content

The exceedance probability curves of liquefaction-induced ground settlement for the three sites are shown in **Figure 3.2**. In this figure, the horizontal axis indicates ground settlement, while the vertical axis indicates the annual exceedance probability. The hazard curve in the figure shows the probability that a certain level of settlement will be exceeded over the course of one year at each site.

The annual exceedance probability curve of Site A falls sharply at a settlement of about 66 cm. Above this settlement level, annual exceedance probability is equal to zero. This is because the ground settlement at Site A hits peaks at 66.84 cm due its soil structure. Likewise, the settlement at Site B is 31.88 cm, while Site C is saturated at 11.61cm. Since the probabilistic seismic hazard curves of the three sites are fairly similar, the differences in the probabilistic liquefaction hazard curves reflect differences in soil structure at each site.



Figure 3.2. Exceedance probability curves of liquefaction-induced ground settlement



Figure 3.3. Exceedance probability curves analyzed by earthquake type at Site A



Figure 3.4. Contribution ratio of earthquake type on exceedance probability curves at Site A

At the annual exceedance probability of 0.2, the ground settlement at Sites A, B, and C are approximately 15 cm, 2 cm and 0.2 cm, respectively. These results suggest that these liquefaction-induced ground settlements are expected at a frequency of once every five years. This result seems to reflect an over-estimation, considering the actual record of liquefaction occurrence in recent decades. Consequently, we conducted a factor analysis with respect to the effect of earthquake type on exceedance probability curve. **Figure 3.3** shows the exceedance probability curves analyzed by earthquake type at Site A. These results can be rearranged as shown in **Figure 3.4**. This figure expresses the contribution ratio of earthquake type on exceedance probability curves at Site A. The contribution ratio of inter-plate earthquakes is almost 0.8. Similar results are obtained from the investigations at Site B and Site C. The results of the factor analysis indicate that earthquakes in the southern capital region whose source faults are unidentified (i.e., upper surface of the Philippine Sea plate and the upper surface of the Pacific plate) play a strong role in increasing annual probabilities of exceedance.

3.2. Probabilistic Liquefaction Hazard Maps

Figure 3.5 shows the probabilistic liquefaction hazard maps of the Tokyo metropolitan area by recurrence interval. The recurrence intervals vary from 10 to 500 years. These values correspond to 0.002 to 0.1 in annual probability of exceedance. The target area is divided into small grids. The size of each grid is approximately 500 m in length and width. Each grid square has a soil structure model provided by the Report on Envisioned Damage Due to an Epicentral Earthquake in Tokyo (Tokyo Metropolitan Government, 1997). White sections indicate areas of ground without sand layers. In other words, these are categorized as non-liquefiable sites. In this figure, differences of color pattern can be seen only along the border between Tokyo and Kanagawa prefectures at the various recurrence intervals. Another area indicates almost same results. In this area, the ground settlements will become saturated up to 50 years in recurrence interval.

Figure 3.6 shows the probabilistic liquefaction hazard maps of the Tokyo metropolitan area by ground settlement. The color coding patterns present that the maps are categorized into two groups. They show that the threshold level of ground surface settlement is around 16 cm. More specifically, the recurrence interval of ground settlement of less than 16 cm is less than 10 years, while the recurrence interval for ground settlement of more than 16 cm is more than 500 years. This phenomenon in the probabilistic liquefaction hazard maps is largely caused by the saturation of ground settlement due to soil structures.



(1) Recurrence interval: 10 years



(3) Recurrence interval: 50 years



(2) Recurrence interval: 20 years



(4) Recurrence interval: 100 years





(6) Recurrence interval: 500 years

Figure 3.5. Probabilistic liquefaction hazard maps by recurrence interval



(1) Settlement of ground surface: 1 cm



(3) Settlement of ground surface: 10 cm







(2) Settlement of ground surface: 5 cm



(4) Settlement of ground surface: 16 cm





Figure 3.6. Probabilistic liquefaction hazard maps by ground settlement

4. CONCLUSIONS

In this study, we proposed a method of evaluating the probabilistic liquefaction hazard based on measures of ground surface settlement. Our fundamental approach was to calculate how much a particular location would settle, and with what probability, based on the location, magnitude, and probability of occurrence of all possible earthquakes. As examples, probabilistic liquefaction hazard curves were estimated for three test sites and probabilistic liquefaction hazard maps of the Tokyo metropolitan area were estimated. The principal results obtained from this investigation are summarized as follows.

- Quantitative evaluation of liquefaction hazard considering the probability in temporal axis can be conducted using the proposed method of probabilistic liquefaction hazard analysis.
- The characteristics of the exceedance probability curve of liquefaction-induced ground settlement are strongly dependent on the soil structure.
- In the Tokyo metropolitan area, the inter-plate earthquakes, especially those from unidentified source faults (i.e., upper surface of the Philippine Sea plate and the upper surface of the Pacific plate), contribute considerably to increase the annual exceedance probabilities of liquefaction-induced ground settlement.
- Based on the probabilistic hazard map of Tokyo by recurrence interval, differences in ground surface settlement at different recurrence intervals are quite small in the eastern part of Tokyo during the variable terms from 10 to 500 years.
- The probabilistic hazard map by ground settlement demonstrates that the recurrence interval for ground settlement of less than 16 cm is less than 10 years, while the recurrence interval for ground settlement of more than 16 cm is more than 500 years.

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