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PROBABILISTIC LIQUEFACTION HAZARD ANALYSIS IN JAPAN

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Abstract: Authors have been proposed a method of evaluating the probabilistic liquefaction hazard based on measures of ground surface settlement. The 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. Generally, the structural damage by liquefaction is mainly causes by ground settlements. Thus, the liquefaction hazard indicated by the ground settlement is more directly to catch on the linkage between the damage and the liquefaction hazard. The settlements of ground surface are calculated from the relationship between the factor of safety for liquefaction (FL value) and post-liquefaction volumetric strain. In this study, we attempt to evaluate a probabilistic liquefaction hazard based on the historical records. Basic concept is comparison between the evaluated liquefaction hazard results and the hysteresis of liquefaction phenomenon.

Introduction

We proposed a method of evaluating the probabilistic liquefaction hazard based on measures of ground surface settlement (Kurita and Fukushima, 2012). The 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. Generally, the structural damage by liquefaction is mainly causes by ground settlements. Thus, the liquefaction hazard indicated by the ground settlement is more directly to catch on the linkage between the damage and the liquefaction hazard. The settlements of ground surface are calculated from the relationship between the factor of safety for liquefaction (FL value) and post-liquefaction volumetric strain (Ishihara and Yoshimine, 1992).

In this study, we carried out a quantitative evaluation of a probabilistic liquefaction hazard analysis. A methodology of the evaluation is comparison between the evaluated liquefaction hazard results and the hysteresis of liquefaction phenomenon. The probabilistic liquefaction hazard curves are computed for the typical sandy ground in Tokyo.

Methodology of Probabilistic Liquefaction Hazard Analysis

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.

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 1. The methods of calculating the liquefaction-induced ground settlement at one site, due to the occurrence of a particular earthquake, are as follows.

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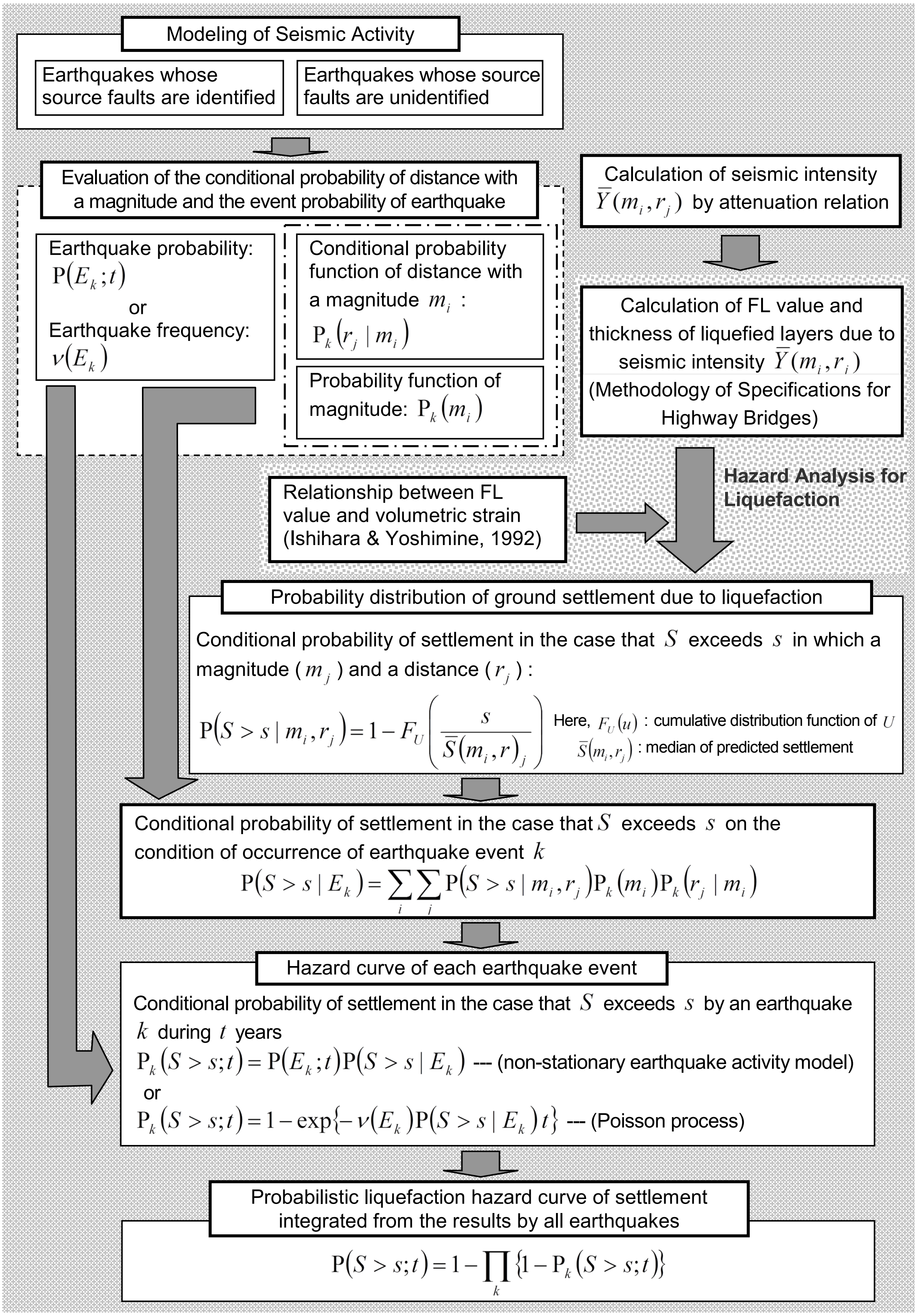

Figure1. Flow of a probabilistic liquefaction hazard analysis focused on ground settlement

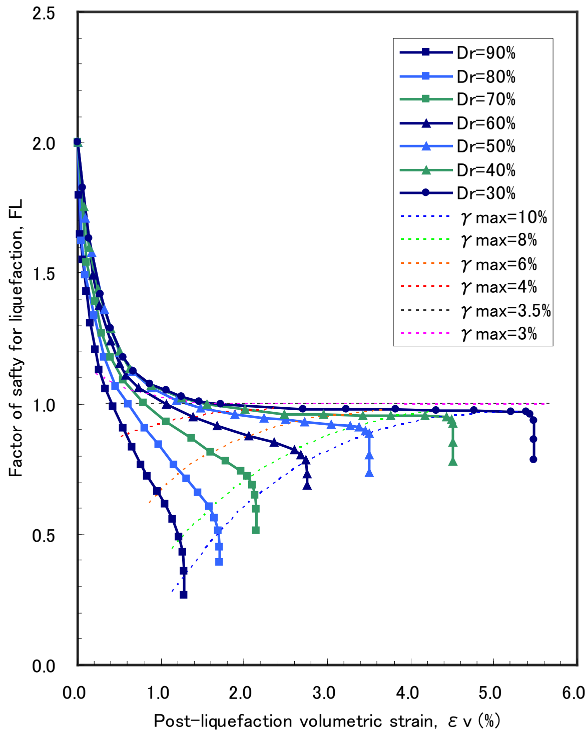

Figure 2. Diagram showing the volumetric strain as a function of the factor of safety (Ishihara and Yoshimine, 1992)

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 Yoshimine(1992). This important relationship is illustrated in Figure 2. Here, D_r and $\gamma_{\max}$ 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.

Historical Liquefaction of Ground in Tokyo

In the lowland of east Tokyo, recurrent liquefaction is reported as Table 1 (Wakamatsu, 2011 and 2012 a). Three major earthquakes induced liquefactions in this area such as Katsushika City and Edogawa City. The details of liquefactions of two older earthquakes are unknown. On the other hand, during the 2011 Tohoku earthquake, maximum ground settlements of Tokyo Bay area is reported as 50 to 60 cm (Wakamatsu, 2012 b).

Table 1. Histrical liquefaction of ground in Tokyo

Earthquake	Date (yyyy/mm/dd)	Magnitude
Ansei Edo Earthquake	1855/11/11	7.0-7.1*
Kanto Earthquake	1923/09/01	7.9
Tohoku Earthquake	2011/03/03	9.0**

* Usami(1996), ** Moment magnitude

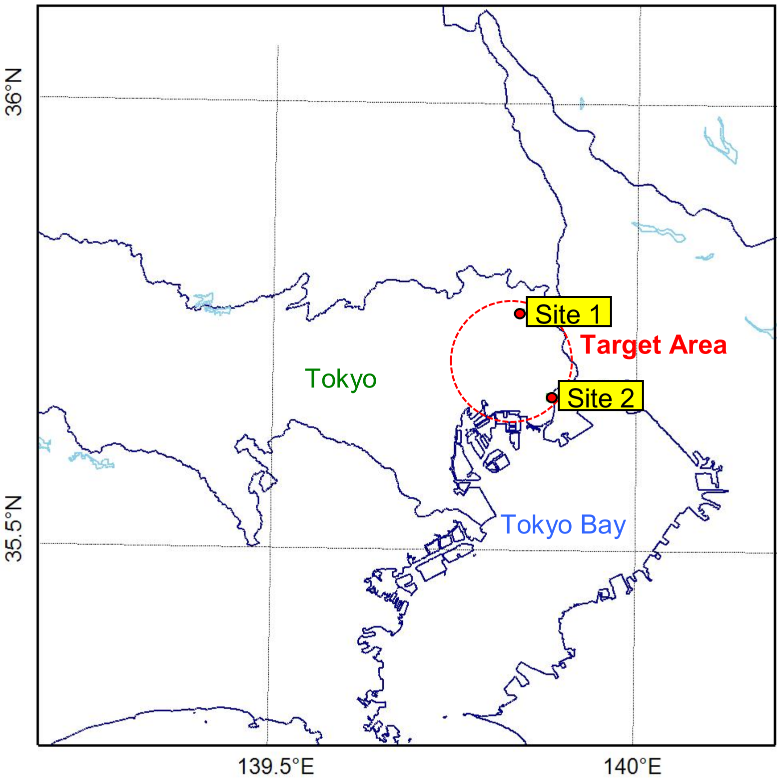

Figure 3. Study area

Table 2. Soil properties of sites studied

(1) Site 1

Layer number	Thickness (m)	Soil type	γt2 (kN/m^3)	γt1 (kN/m^3)	D50 (mm)	FC (%)	SPT N value
1	6.0	alluvial sand	16.677	14.715	0.35	10	5
2	14.0	alluvial clay	14.715	12.753	0.04	65	1
3	5.0	Diluvial sand	17.658	15.696	0.35	10	20
4	10.0	diluvial clay	16.677	14.715	0.04	65	20
5	5.0	diluvial gravel	19.620	17.658	2.00	0	50
6	-	Edogawa layer	20.601	-	-	-	above 50

(2) Site 2

Layer number	Thickness (m)	Soil type	γt2 (kN/m^3)	γt1 (kN/m^3)	D50 (mm)	FC (%)	SPT N value
1	6.0	alluvial sand	16.677	14.715	0.35	10.0	5
2	14.0	alluvial clay	14.715	12.753	0.04	65	1
3	15.0	alluvial clay	15.696	13.734	0.04	65	5
4	15.0	diluvial sand	18.149	16.187	0.35	10	30
5	-	Edogawa layer	20.601	-	-	-	above 50

Note: γt1: volume density above groundwater level, D50: mean particle diameter
γt2: volume density below groundwater level, FC: fine fraction content

Comparison of Probabilistic Liquefaction Hazard

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. The soil properties of each site are listed in Table 2. 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.

The exceedance probability curves of liquefaction-induced ground settlement for the two sites are shown in Figure 4. In this figure, the horizontal axis indicates ground settlement, while the vertical axis indicates the annual exceedance probability. The hazard curves in the figure show the probability that a certain level of settlement will be exceeded over the course of one year at each site.

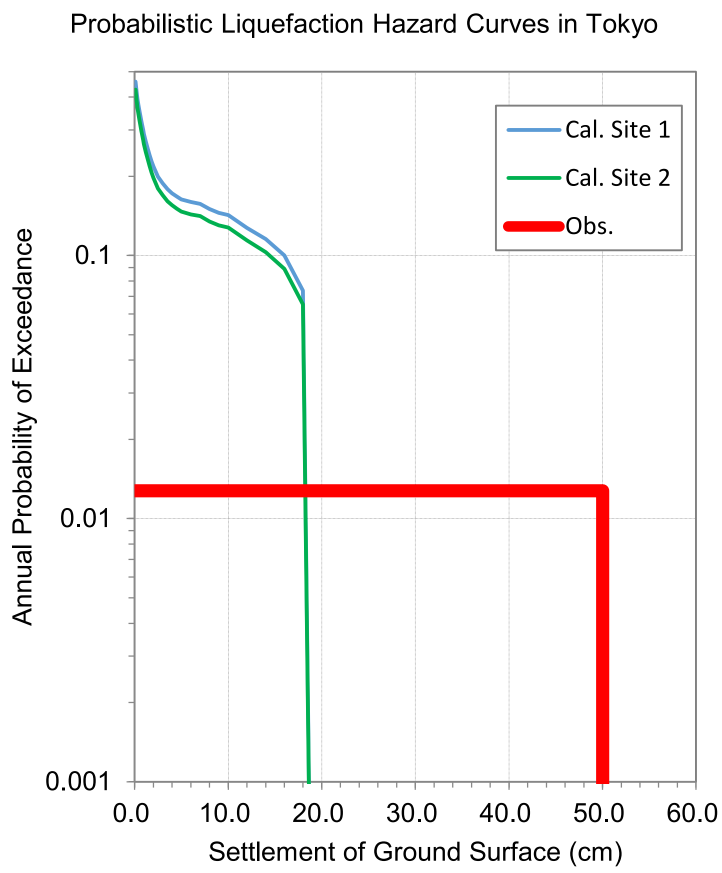

Figure 4. Exceedance probability curves of liquefaction-induced ground settlement

From Table 1 a recurrent interval of liquefaction based on the historical records is calculated as 78 years. The annual exceedance probability of occurrence of liquefaction based on the assumption of Poisson distribution is 0.0127. The assumed ground settlements of 50 to 60 cm are employed according to the experience of the 2011 Tohoku Earthquake, since the detailed information regarding the ground settlements of older earthquakes is unknown. This observed exceedance probability based on the historical liquefaction is also plotted by red thick line in Figure 4.

The calculated exceedance probability curves are overestimated in the small range of ground settlements. On the other hand, reverse phenomenon can be seen in the large range of ground settlements, because calculated results are saturated at 18cm. Therefore, observed results are in between the calculated results on the whole.

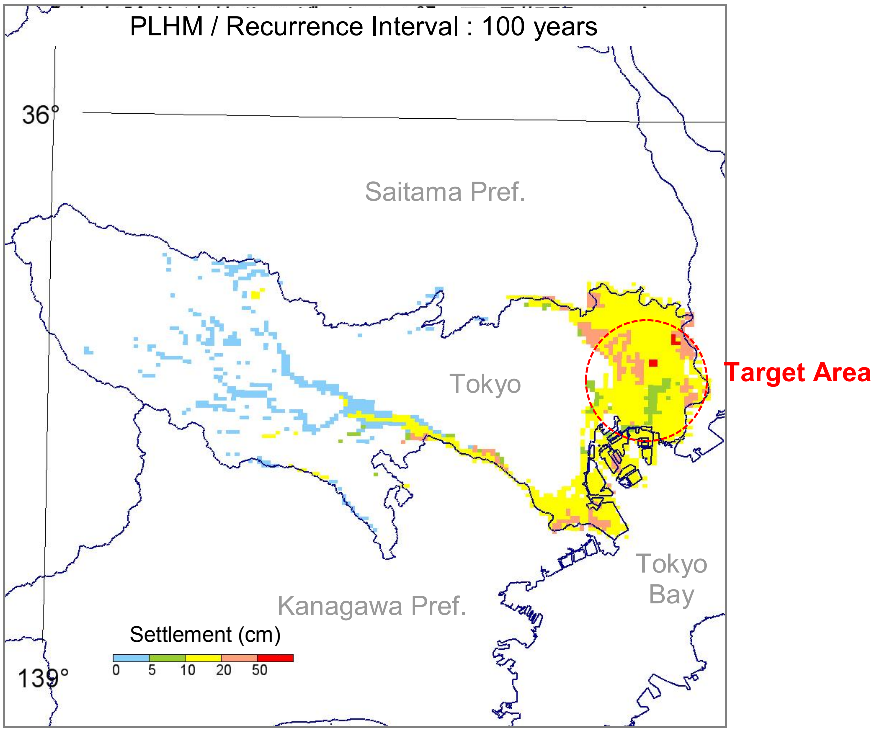

Figure 5. Probabilistic liquefaction hazard maps by recurrence interval

Figure 5 shows the probabilistic liquefaction hazard maps of the Tokyo metropolitan area by recurrence interval. The recurrence interval is 100 years. 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.

One hundred years exceedance probability of occurrence of liquefaction based on the historical data is 0.722. The estimated ground settlements of historical liquefaction are within 50 to 60 cm. These observation results are consistent with the calculated results in the target area in Figure 5.

Conclusions

We conducted an evaluation of probabilistic liquefaction hazard based on the historical records. The probabilistic liquefaction hazard curves were computed for the typical sandy ground in Tokyo. Then, comparison between the calculated liquefaction hazard results and the hysteresis of liquefaction phenomenon was carried out.

The observation results based on the historical liquefactions are consistent with the calculated results in the target area. It is confirmed that the obtained probabilistic liquefaction hazard curves are informative and helpful for the disaster reduction.

Acknowledgements
This study uses the dataset of the seismic activity model published on the website of the Japan Seismic Hazard Information Station (J-SHIS, which is managed by the National National Research Institute for Earth Science and Disaster Prevention). Soil property data in Tokyo metropolitan area was provided by the Tokyo Metropolitan Government. The authors extend deep gratitude to all those involved.

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