Precision of Real-Time Estimation of Liquefaction Potencials During the 2011 Off the Pacific Coast of Tohoku Earthquake

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SUMMARY:
The coast area in Tokyo-wan which is far from the earthquake fault, were heavily liquefied during the 2011 off the Pacific coast of Tohoku earthquake. It is very important to predict the occurrence and degree of liquefaction, because the liquefaction affects the safety of underground pipelines and facilities of roads and ports. The real-time disaster prevention system "SUPREME" is established and used by Tokyo Gas supply system in order to secure the safety. The system collected the SI value from 4,000 sensors, calculated the distribution of SI value, liquefaction potential, damages of pipelines for about 20 minutes after the earthquake. In this paper, it is shown that estimated liquefaction area corresponds actual liquefaction area very well, and the reason is that "SUPREME" uses very dense SPT data and SI sensors and the estimate method of liquefaction considers the effect of duration time of earthquake ground motion.

Keywords: liquefaction, P_L value, real-time damage estimation, gas supply system, GIS

1. INTRODUCTION

Real-time disaster prevention system "SUPREME" was established by Tokyo Gas Co., Ltd. aiming at rapid emergency response to disaster (Shimizu et al., 2006). This system can monitor seismic motion using New SI(spectrum intensity) sensors installed at 4,000 locations in its supply area. Once earthquake occurs, it instantly estimates the distribution of seismic motion, liquefaction potential and damage of underground pipelines. In the pipelines damage estimation, damage location number is calculated in each 50m square grid by multiplying pipeline length(km) and damage ratio (number / km) which is calculated from empirical formula using such primary factors as SI value, pipeline type, ground type and liquefaction occurrence. Among these factors, it is particularly important to estimate liquefaction occurrence precisely because the Tokyo Bay area has vast soft ground such as reclamation land. From these backgrounds, Ishida et al. (2009) prepared liquefaction table for every 50m square grid using boring data, and proposed the liquefaction estimation method considering seismic duration time. Tokyo Gas also has proceeded to apply this method to SUPREME.

In the 2011 off the Pacific coast of Tohoku earthquake, though the Tokyo Bay area is far from the epicenter and peak ground acceleration was around 200 cm/s^2, liquefaction has occurred vastly in this area. This is considered due to its quite long seismic duration time, which is just what Ishida et al. (2009) considered.

Therefore, this paper verifies proposed liquefaction estimation method using SI value by comparing actual distribution of liquefaction and the estimation result. The target area of verification is set at Mihama-ku, Chiba-city, where was liquefied most heavily in the supply area.

2. SUMMARY OF THE LIQUEFACTION POTENTIAL ESTIMATION METHOD

Liquefaction Index Number (P_L Value) is calculated from following equation:

$$P_L = \int_0^{20} (1 - F_L)(10 - 0.5x)dx \qquad (2.1)$$

where x is the depth from ground surface(m) and F_L is resistibility against liquefaction(F_L Value). F_L is calculated for each depth as follows:

$$F_L = \frac{R}{L} \quad \cdots \quad \begin{cases} F_L \leq 1.0\text{: judged as liquefied} \\ F_L > 1.0\text{: judged as not liquefied} \end{cases} \qquad (2.2)$$

where R is dynamic shear strength ratio, L is seismic shearing stress ratio. R can be calculated from following compensated equation using soil cyclic triaxial strength ratio (R_L).

$$R = c_W R_L \qquad (2.3)$$

where c_w is calibration coefficient depending on seismic motion, which is categorized at Specifications for Highway Bridges as follows:

(TYPE1 : In case of the seismic motion of interplate earthquake)

$$c_W = 1.0 \qquad (2.4)$$

(TYPE2 : In case of the seismic motion of inland earthquake)

$$c_W = \begin{cases} 1.0 & (R_L \leq 0.1) \\ 3.3R_L + 0.67 & (0.1 < R_L \leq 0.4) \\ 2.0 & (0.4 < R_L) \end{cases} \qquad (2.5)$$

On the other hand, the liquefaction potential estimation method in SUPREME improves that of Specifications For Highway Bridges from the aspects of 1) Evaluation of L value, 2) Evaluation of c_w, 3) Consider the characteristic of Tokyo east lowland area, as follows:

1) Evaluation of Seismic Shearing Stress Ratio, L

As the seismic motion indicator to evaluate L in Eqn.2.2, proposal method uses SI value instead of peak ground acceleration, as following equation:

$$L = 0.01 \frac{SI}{(\sigma_v')^{0.1}} \qquad (2.6)$$

where σ_v' is effective overburden pressure(kgf/cm^2) and SI is SI value(kine). This improvement considers the following two points. Firstly, recently peak ground acceleration records near epicenter can be more obtained than those times when F_L Method was installed to Design Method. If these records are applied to design seismic intensity, liquefaction potential tends to be overestimated. Secondly, shearing stress and liquefaction potential are influenced by period and repeat count than peak ground acceleration.

2) Evaluation of c_w representing the coefficient value of seismic motion characteristic

The coefficient value of seismic motion characteristic (c_w) is given as follows:

$$c_w = \frac{0.6}{B_T \times B_R} \quad (2.7)$$

$$B_T = 0.134 + 0.340 \times \log_{10} T_D \quad (2.8)$$

$$\log_{10} B_R = \frac{R_L - 0.20}{0.45 - 0.20} \times \log_{10} 0.673 \quad (2.9)$$

$$T_D = 10^{0.3M_j - 1.0} + 10^{0.17M_j + 0.54 \log X_{eq} - 0.6} (\log_{10} 2) \quad (2.10)$$

where, B_T : amplitude conversion coefficient considering soil-tightness
B_R : amplitude conversion coefficient considering duration time
T_D : duration time of seismic motion(sec)
M_j : Magnitude of Japan Meteorological Agency
X_{eq} : equivalent hypocentral distance(km)

In Eqn.2.10 based on aging characteristics formula of Noda et al. (2002), duration time which affects liquefaction is considered from the start of strong motion to the point where the envelope amplitude declines to the half(Fig 2.1). In addition, the SUPREME system substitutes focal distance for X_{eq} instead of equivalent hypocentral distance, due to the difficulty in instant calculation of equivalent one.

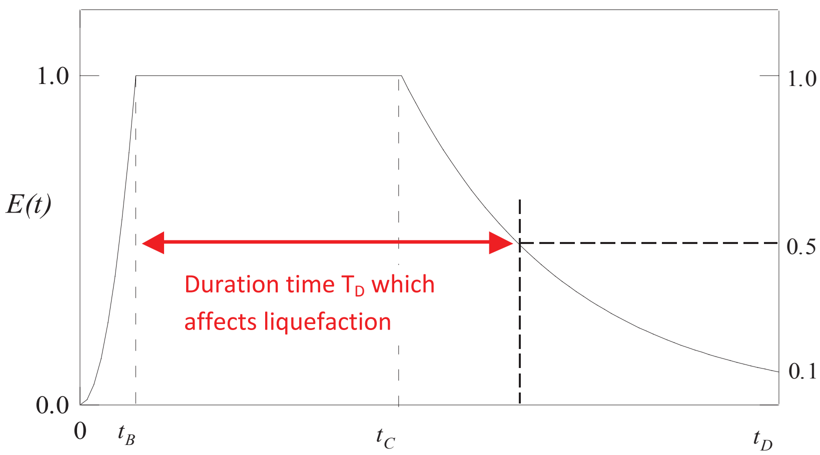


Figure 2.1. Duration time T_D which affects liquefaction

3) Consider the characteristic of Tokyo east lowland area

Proposal method uses the criterion formula (Kamei et al., 2002) considering the characteristic of alluvial sandy soil in Tokyo lowland area. That soil has many fine soils, which has characteristic that liquefaction potential is high despite of its low N-value.

3. LIQUEFACTION ESTIMATION IN THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTUQUAKE

In the 2011 off the Pacific Coast of Tohoku Earthquake, SUPREME collected the SI value from about 4,000 sensors within 10 minutes after earthquake occurrence, and finished the simulation of the damage estimation within 20 minutes. The liquefaction estimation in this simulation did not introduce c_w, but this paper examines on the assumption that c_w was introduced.

In the 2011 Earthquake, the earthquake magnitude announced by Japan Meteorological Agency was revised in stages as **Table 3.1**.

Table 3.1. Magnitude revision by Japan Meteorological Agency

M	announcement time	notes
7.9	3/11 14:50	prompt report
8.4	3/11 16:00	the 1st report
8.8	3/11 17:30	the 3rd report
9.0	3/13 12:55	the 15th report

Since this paper presupposes an instant estimation, the examine picks up M=7.9 case basically, but also picks up M=9.0 case for further improvement. In M=9.0 case, conditions are extrapolated considering that Eqn.2.10. is the equation for the Magnitude of Japan Meteorological Agency. Therefore this paper focuses only tendency based on difference of magnitude.

Table 3.2 shows the difference of c_w in some methods. Specifications for Highway Bridges set c_w to 1.0, Yoshida et al. (2009), set 0.5 in massive earthquake and Tokimatsu and Yoshimi (1983) set less than 1.0. In case of Eqn.2.7, c_w is 0.80 in M=7.9 and 0.72 in M=9.0, which are low values.

Table 3.2. The difference of c_w in some methods

methods	conditions	c_w
Specifications for Highway Bridges	inter plate earthquake	1.0
Yoshida et al.,	massive earthquake	0.5
Tokimatsu and Yoshimi	M=7.9	0.94
	M=9.0	0.81
Ishida et al., (X_{eq}=350km)	M=7.9	0.80
	M=9.0	0.72

Fig. 3.1 shows the distribution of SI value for each 50m square grid estimated complementarily from SI data of 4,000 sensors. SI value in the southern part of Ibaraki prefecture exceeds 40 kine, that in Chiba generally exceeds 30 kine and that in the most of area from Tokyo to Yokohama is lower than 30 kine.

Fig. 3.2 shows the distribution of duration time calculated from Eqn.2.10. Figure 3.2(a) shows the result inputted 7.9 into M_j and Figure 3.2(b) inputted 9.0. Few seconds differ between Ibaraki and Kanagawa, so duration time seems not depend on distance. On the contrary, the result of M=9.0 is about two times as long as that of M=7.9. That of M=9.0 corresponds better to actual duration time.

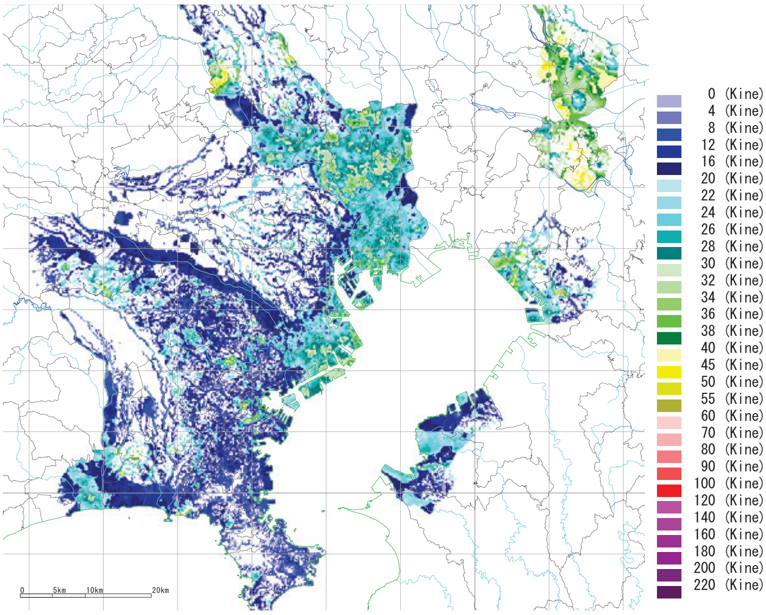
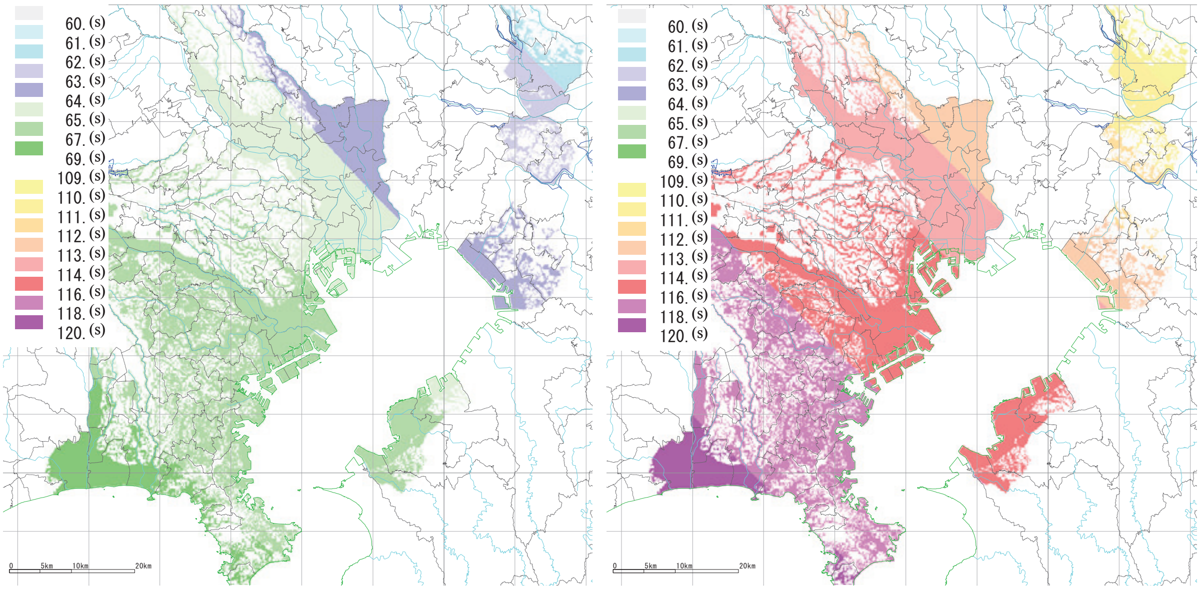


Figure 3.1. Estimated map of SI values using observed values from about 4,000 sensors



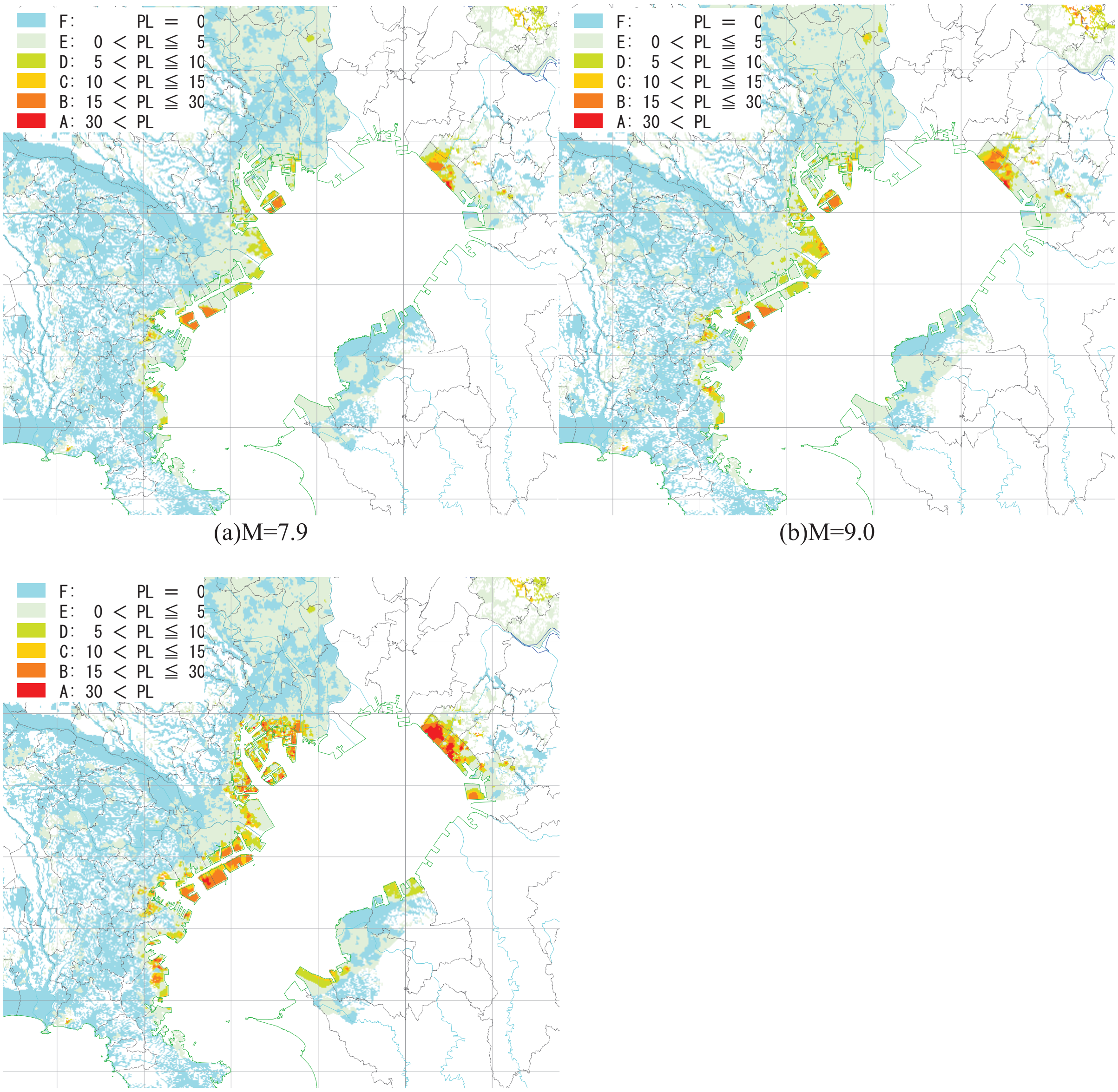
(a)M=7.9 (b)M=9.0

Figure 3.2. Estimated map of duration time by eqn.2.10

Fig. 3.3 shows the distribution of estimated SI value and that of P_L value estimated from liquefaction table, which was prepared in advance as stated in Chapter.2. Though it is not critical, the area where P_L value exceeds 10 becomes wider in the case of M=9.0. This is because c_w value changed by considering the affect of duration time.

Generally estimated value and actual liquefaction results correspond well, but there are two areas where they do not correspond well. One is Daikoku Wharf area, where SI value is high despite there was no liquefaction. This indicates that to check the existence of liquefaction countermeasure is necessary for the improvement of the precision. The other area is Kodukue(Kouhoku-ku) and Shibacho(Kanazawa-ku) of Yokohama City. Liquefaction has occurred in this area though estimated liquefaction potential is low. This is because there are no boring data in this area despite SUPREME uses boring database which covers 60,000 locations. In addition, these areas are not natural but artificial ground. From these differences, it seems effective for the improvement of precision to collect more geological data.

Figure 3.3(c) shows the result of calculation using old data before the revision of reclamation land. Liquefaction potential is overestimated in this case, therefore precision of estimation in M=7.9 improves with this revising. This means that the revision of reclamation land data is necessary for the improvement of precision.



(a)M=7.9

(b)M=9.0

(c)condition before the revision of reclaimed land (M=7.9)

Figure 3.3. Estimated map of P_L values

4. VERIFICATION IN BAY AREA OF CHIBA CITY

This chapter verifies the proposal liquefaction estimation method on the bay area of Chiba City, where severe liquefaction occurred in 2011 earthquake.

Fig. 4.1 shows the distribution of complementarily estimated SI value in each 50m square grid. Estimated value at K-NET Inage is 33.4 kine, and that at K-NET Chiba is 25.1kine. Compared to observed value, these values are correct within less than 20 percent.

Fig. 4.2 shows the correspondence between the result of proposal liquefaction estimation and actual liquefaction occurrence. Actual occurrence data is from two researches. Firstly, Yasuda and Harada indicated the seemingly liquefied area through a field survey and an aerial photograph. Secondly, Ministry of Land, Infrastructure, Transport and Tourism and The Japanese Geotechnical Society also released the liquefaction map. Severe liquefaction occurred in Mihama-ku, but liquefaction in Chuo-ku was limited. Estimation result corresponds to this tendency well.

Fig. 4.3 shows the boring data in Mihama-ku and Chuo-ku. Compared to No.2(Chuo-ku) data, No.1(Mihama-ku) data has some geological conditions which is likely to be liquefied, which are 1) ground-water level is lower, 2) N value of earth filling up to 4m is smaller, 3) N value of alluvial sand layer under 4m is around 10. Other boring data has similar geological tendency in each area, so the difference between Mihama-ku and Chuo-ku is caused by geological difference. It is also due to the geological difference that estimated SI value at Mihama-ku is a little bigger than that at Chuo-ku in Fig. 4.4.

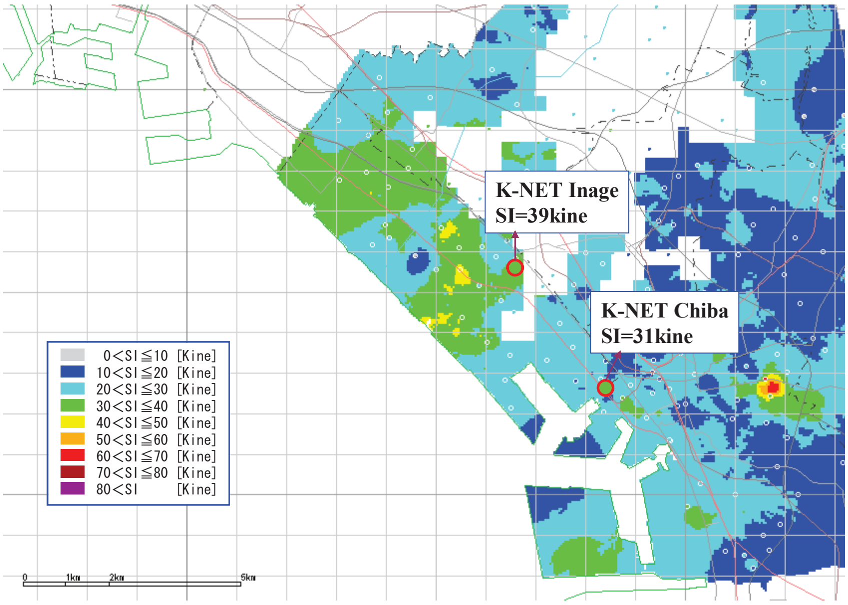


Figure 4.1. Map of SI values estimated at the coast area in Chiba city

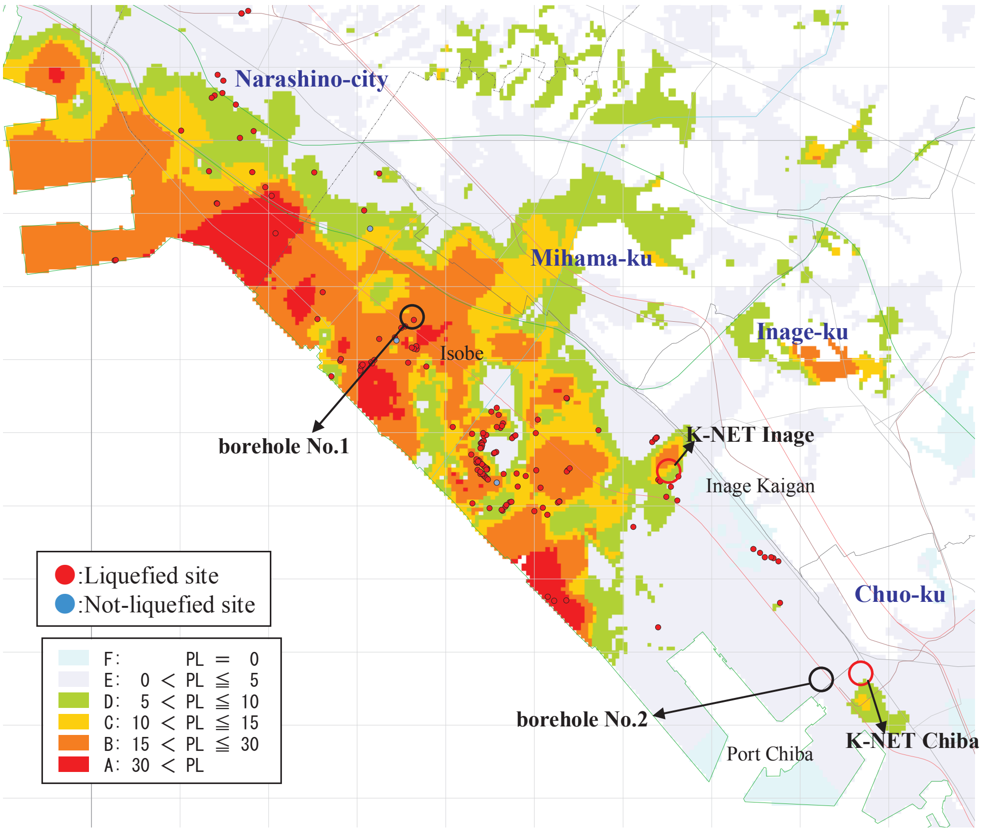
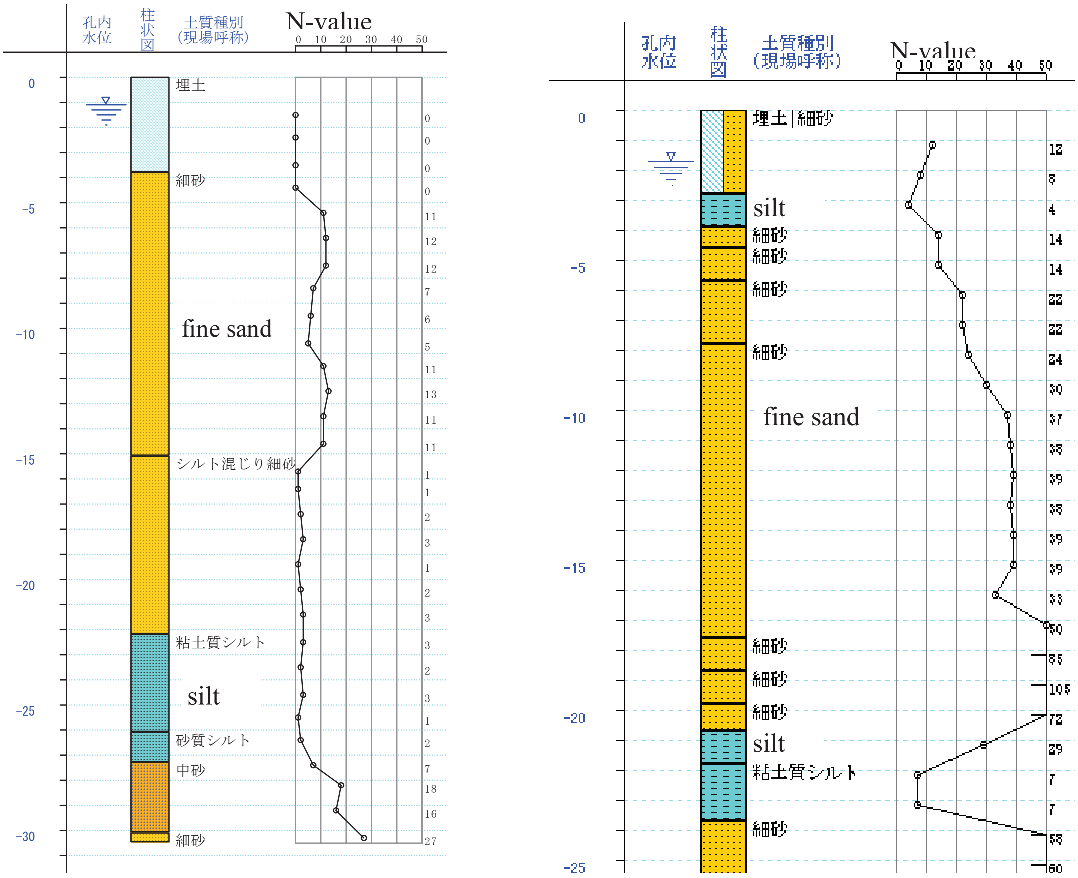


Figure 4.2. Comparison of liquefied area and estimated area during the Pacific coast of Tohoku at the coast area in Chiba city

Circles are liquefied sites examined by Ministry of Land, Infrastructure, Transport and Tourism.



(a) No.1 (b)No.2

Figure 4.3. N-values and geology and by borehole data

Non-stationary spectrum of observation record in K-NET Inage is shown at Fig. 4.4, and that in K-net Chiba is shown at Fig. 4.5. K-NET Inage is the seismic observation point where the occurrence of liquefaction is identified, and K-NET Chiba is not identified. The estimated P_L value (in case of M=9.0) is 25.1 in K-NET Inage and 1.3 in K-NET Chiba. As marked by red arrow, predominant period in K-NET Inage drastically changes from 0.6 sec to 1.0 in the time between 110 sec and 120 sec, and liquefaction seems to occur at around 120 sec. In contrast, the change of predominant period with time in K-NET Chiba is small. Fukutake and Cho have reported that liquefaction occurred after principal motion by effective stress analysis in the ground of Urayasu City. Based on these factors, liquefaction seems to be closely related with the aging change of predominant period in observation record.

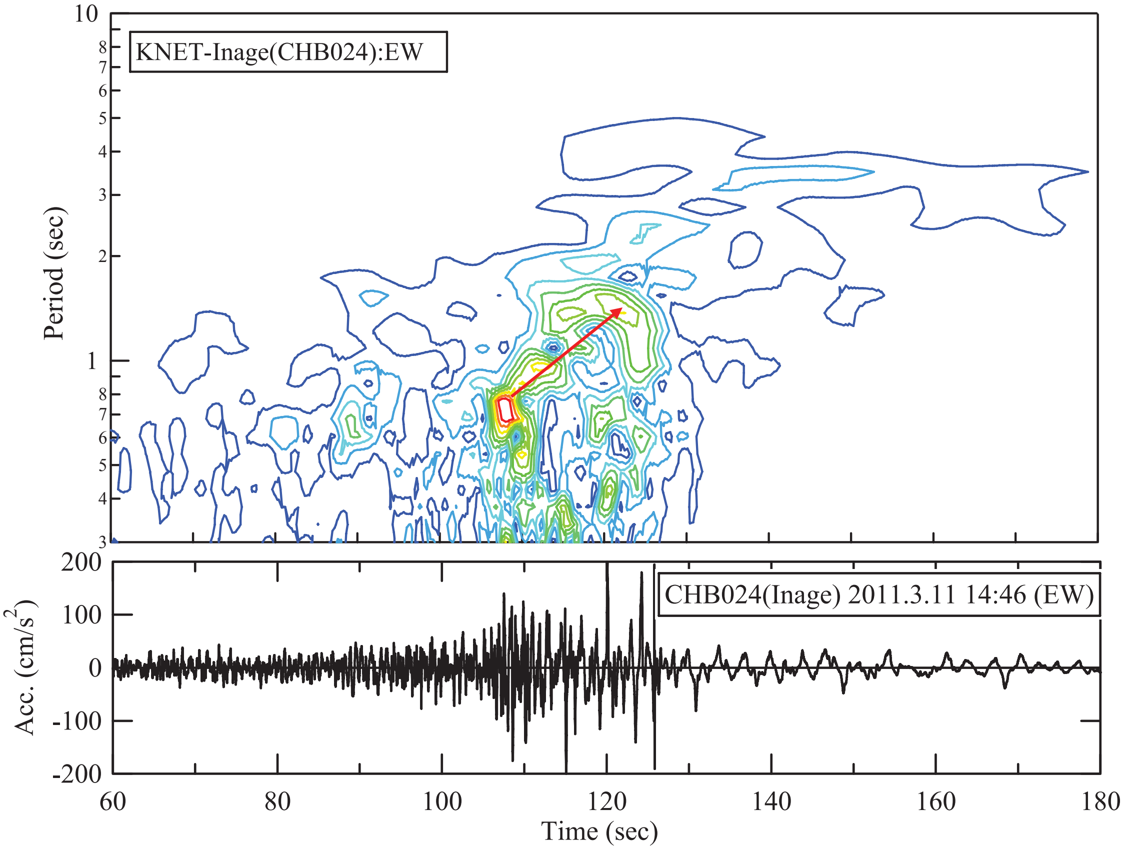


Figure 4.4. Non-stationary spectrum of observed record at K-NET Inage (EW comp.)

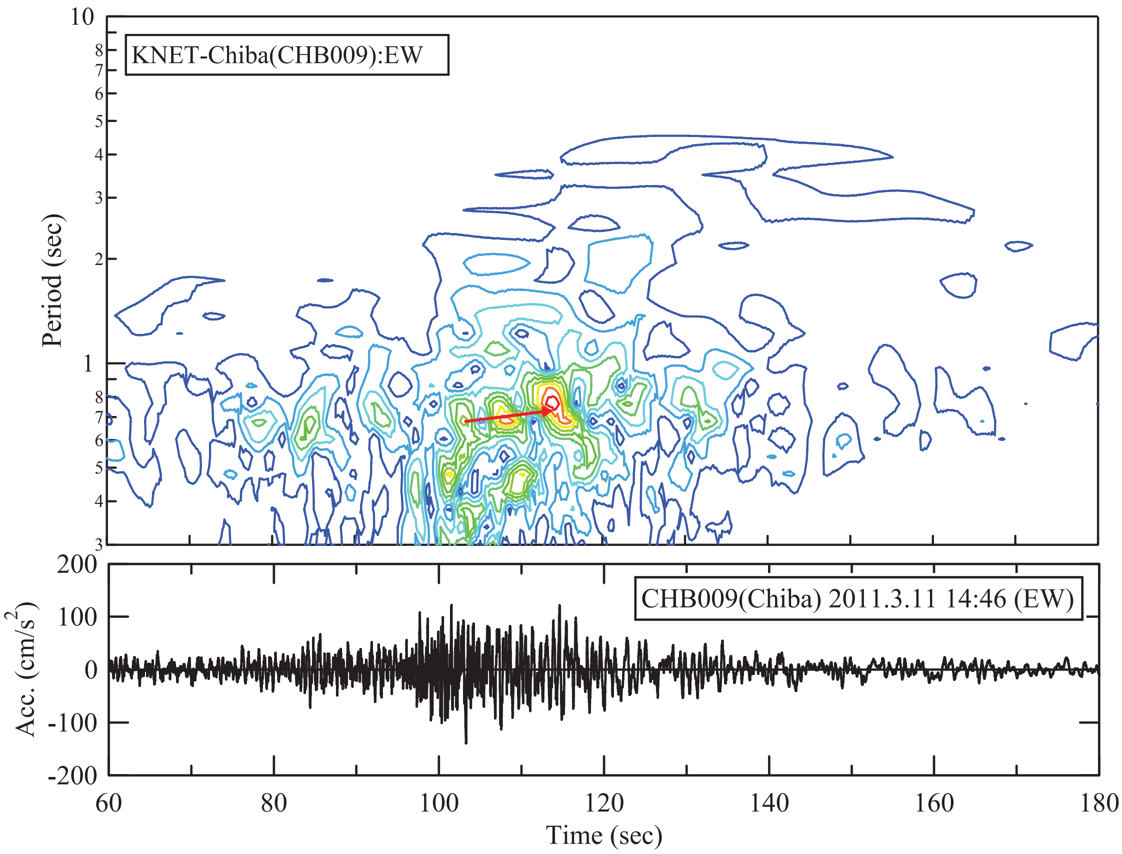


Figure 4.5. Non-stationary spectrum of observed record at K-NET Chiba (EW comp.)

5. CONCLUSIONS

In the 2011 off the Pacific coast of Tohoku earthquake, real-time disaster prevention system "SUPREME" which was established by Tokyo Gas Co., Ltd. estimated the distribution of SI value, liquefaction potential and damage of pipelines in about 20 minutes, by using observation record of about 4,000 locations. Then those estimated data has been served to the 1st headquarters meeting which was held 30 minutes after the earthquake occurrence. This paper verifies the liquefaction estimation method on bay area in Chiba City, and shows that estimated liquefaction area corresponds actual liquefaction area very well.

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