Damage of Oil Storage Tanks Caused by Liquid Sloshing in the 2003 Tokachi Oki Earthquake and Revision of Design Spectra in the Long-Period Range

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ABSTRACT :

The 2003 Tokachi-oki earthquake (Mw=8.0) caused the severe damage to oil storage tanks such as fires and sinking of floating roofs by liquid sloshing excited by long-period strong ground motions. In order to prevent such severe damage due to future earthquakes, we predicted the velocity response spectra in the long-period range at more than 80 oil industrial complex districts in Japan, mainly based on the empirical method considering seismotectonic zoning. Based on both predicted spectra for earthquakes with maximum expected magnitude in each seismotectonic zone and damage pattern of oil storage tanks, we proposed design spectra with 210 cm/s in maximum as a function of period and district, which were adopted in the revised Japan Fire Service Law enforced on April 2005.

KEYWORDS: Long-period ground motion, Liquid sloshing of oil storage tank, Tokachi-oki earthquake, Design spectrum

1. INTRODUCTION

The 2003 Tokachi-oki earthquake (Mw=8.0) occurred on 26 September, east off Hokkaido, north of Japan, and caused two disappeared by tsunami and more than one hundred collapsed houses. Considering its magnitude, the extent of damage is not so large. On the other hand, oil storage tanks in and around Tomakomai, a coastal city in southern Hokkaido, were severely damaged by liquid sloshing in spite of 225km of the epicentral distance. Especially in the Idemitsu Refinery, two tank fires broke out and seven floating roofs sank, and 30 tanks suffered some amount of damage such as overflow and splash of oil, deformation of rolling ladder, weather shield, guide pole, gauge pole and air foam dam and so on.

Fire and Disaster Management Agency (FDMA) and we have investigated the damage of oil storage tanks and cause of tank fires, and also investigated characteristics of seismic ground motions near the tank sites. In this paper, the investigation results are briefly described. Based on the relation between damage and ground motion characteristics in the 2003 Tokachi-oki earthquake, seismic design spectra for liquid sloshing of oil storage tank in the Fire Service Law in Japan was revised in order to prevent the damage due to earthquakes in the near future.

2. LIQUID SLOSHING OF OIL STORAGE TANK

According to the velocity potential theory with rigid tank, natural period Ts of sloshing is given by Eqn.2.1.

$$T_S = 2\pi\sqrt{\frac{D}{2g\varepsilon_1}\coth\left(2\varepsilon_1\frac{H}{D}\right)} \tag{2.1}$$

where g is the acceleration of gravity and ε_1 is 1.841. D is a tank diameter and H is liquid height. Maximum sloshing height η_{max} can be expressed by the following equation using the velocity response spectrum Sv at a period of Ts:

$$\eta_{\max} = 2.6295 \frac{D}{gT_S} S_V \tag{2.2}$$

Eqn.2.2 means that Sv is decisively important to estimate liquid sloshing. According to the regulation in Fire Service Law of Japan enforced in 1983, the velocity response spectrum Sv is assumed constant, that is, about 100 cm/s (damping factor = 0.5%) in the long-period range and in the whole of Japan.

3. CHARACTERISITICS OF SEISMIC GROUND MOTIONS IN THE 2003 TOKACHI-OKI EARTHQUAKE

Japan has installed many seismometers such as K-NET after the 1995 Hyogo-ken Nanbu earthquake. Figure 1 shows the velocity waveforms along the coast from Erimo observatory closest to the epicenter to in and around Tomakomai where many oil tanks were severely damaged. PGV at Erimo is 0.12m/s, but the one at Tomakomai is 0.35m/s in spite of large distance (about 230km) from the epicenter. Furthermore, long-period ground motions predominate and duration time becomes larger at Tomakomai. Such features of ground motions are considered as the influence of the thick sediment of Yufutsu Plain in and around Tomakomai (Aoi et al. 2004). Sv calculated from the records in and around Tomakomai showed larger than the regulation value (about 100 cm/s) at that time in the period range from 5 to 10 sec. as shown in Fig.2.

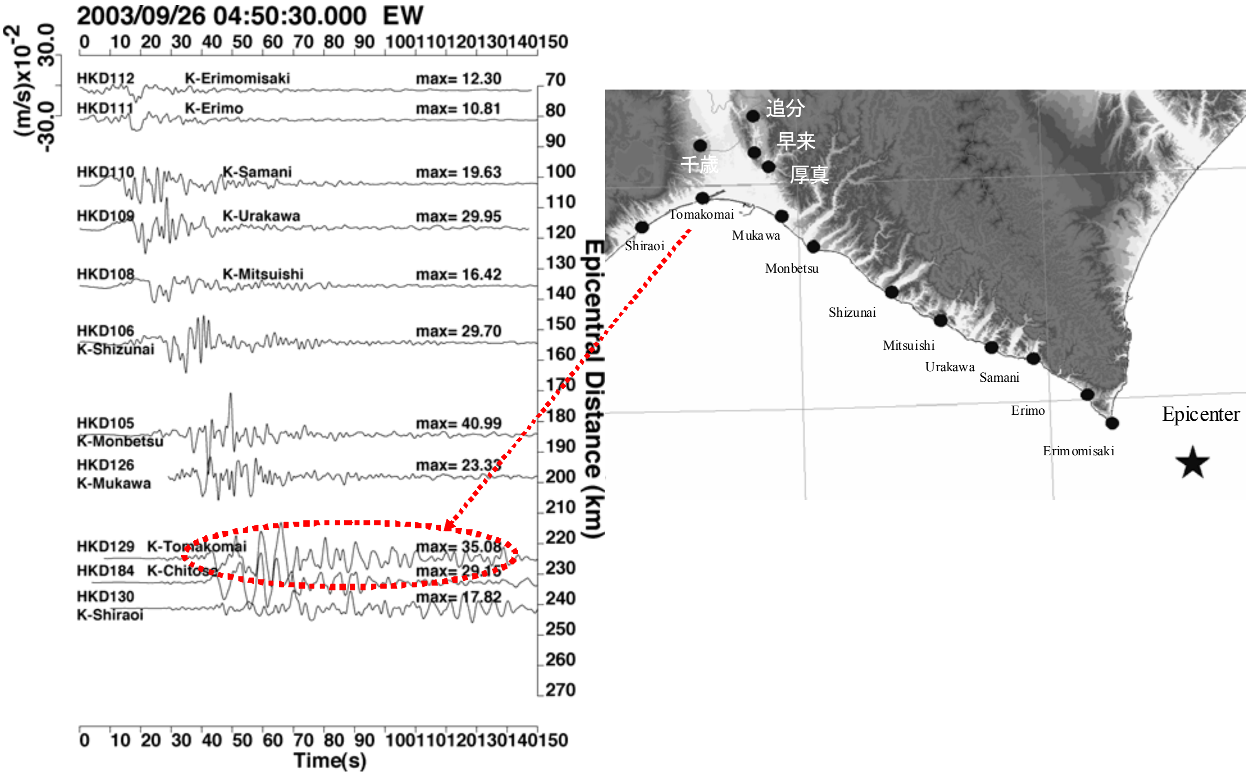


Figure 1 Velocity waveforms along the coast from the nearest K-NET station to the epicenter to in and around Tomakomai

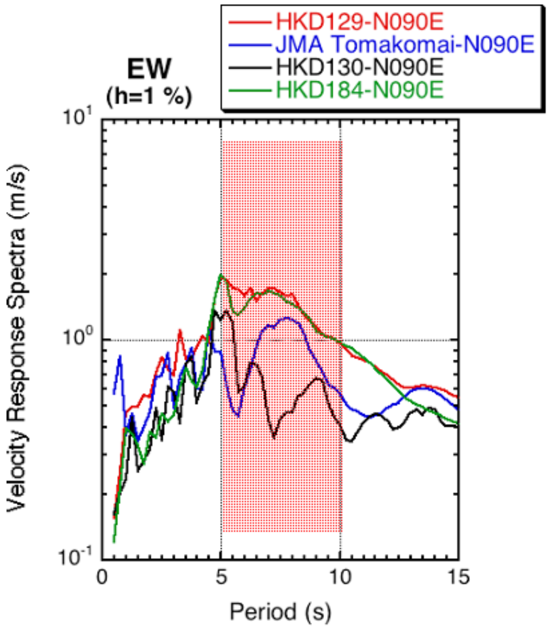


Figure 2 Velocity response spectra in and around Tomakomai

4. HEAVY DAMAGE OF OIL TANK AND ITS CAUSE

Two tank fires occurred. One is a ring fire between the floating roof and the shell plate. According to Nishi and Yokomizo (2006), the cause of the ring fire is the spark at the collision between the roof and the equipments for support of the guide and the gauge pole above the top angle. Another fire of naphtha tank that became full-surface fire, occurred after two days of the earthquake (Fig.3) and continued for 44 hours although best fire brigades could do. Until the fire breakout from the event, fire foam had been dropped on the oil surface in order to prevent fire breakout, because the floating roof sank and naphtha was exposed in atmosphere. It has been inferred that covering by the foam was not complete and isolated foam accumulated electricity while the fire foam went down into the vapor and then sparks came off between isolated foam and the shell plate (Nishi and Yokomizo, 2006). Furthermore, there were seven tanks of which floating roofs sank, overflow of oil from some tanks, large amount of oil spilt on floating roofs, outflow of oil through the drainpipe, deformation or failure of gauge pole, guide pole, rolling ladder, roof or its rafter, weather hood, foam dam, and so on, because of large sloshing excited by the unexpected long-period strong ground motions observed in and around Tomakomai.

Figure 3 Tank fire occurred after two days of the event
(photo by Fire and Disaster Management Agency)

5. RELATION BETWEEN MAXIMUM SLOSHING WAVE HEIGHT AND DAMAGE IN TOMAKOMAI

Since there were not so much data about maximum sloshing wave height η_{max}, we calculated η_{max} for all tanks in Tomakomai shown in Fig.4, applying the two dimensional response analysis method (Zama, 1985) to seismic records at tank sites, after confirming the accuracy through the comparison between estimations and observations, assuming appropriate damping for each roof-type tank (CRT: corn roof tank=0.1%, CFRT: covered floating roof tank=0.5%, FRT(s): single-deck floating roof tank=0.5%, FRT(w): double-deck floating roof tank=1.0%). Estimated η_{max} exceeds 2m at the periods of 3.5 to 9 sec, and especially exceeding 3m at the periods of 5 and 7.5 sec. Closed symbols show tanks with some damage. Severely damaged tanks such as fire and sank of floating roof, are enclosed by large circles in the figure, which are almost under the conditions that η_{max} is over 2m and Ts is longer than 7 sec.
On the other hand, there were two floating roof tanks of 100,000kl crude oil storage in these severely damaged tanks, although η_{max} is at the highest about 1.3m. The tank diameter is 78.2m, the shell height is 24.5m, and the liquid height was 14.414m at that of the earthquake, and the sloshing natural period T_1 was 12.0 sec, the one of 2nd mode T_2 was 5.5 sec. The sloshing mode at a certain time in the 2-D sloshing analysis for the case of without floating roof, namely free surface, indicates more than 1m in high at about one-third of radius from the center. It is considered that the large wave height at this portion was brought by the second mode of sloshing, because the Sv value at T_2 is very large as shown in Fig.2. Yamauchi et al. (2006) concluded that the buckling of pontoons or failure of the joint between deck and pontoon were caused by the large deformation of deck due to the second mode of sloshing, on the basis of the detail FEM analysis by the LS-DYNA which can treat the interaction between fluid and floating roof (Miura, 2004).

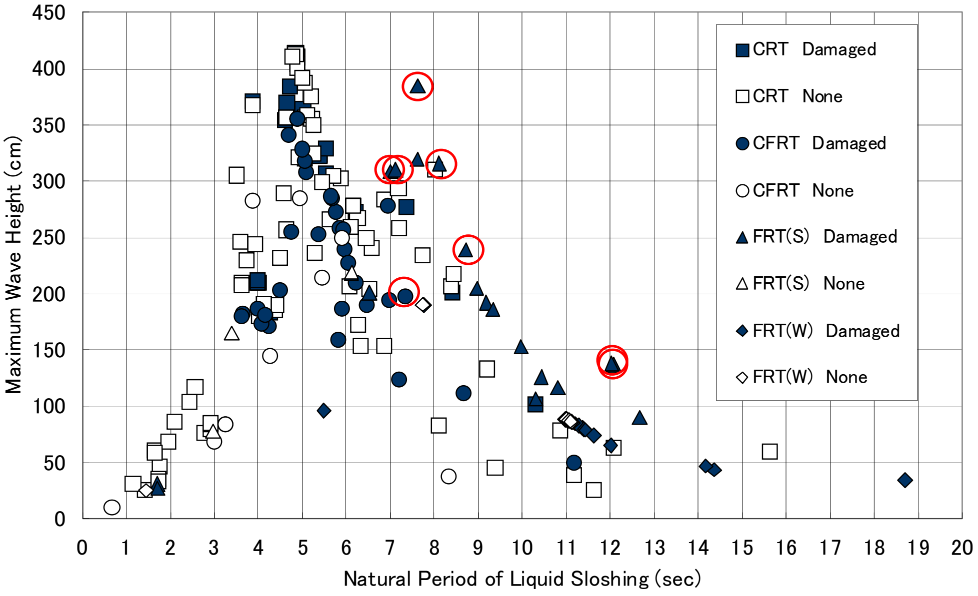


Figure 4 Estimated maximum sloshing wave height at Tomakomai.

6. SPECIFIED DESIGN SPECTRA AT TANK SITES

As mentioned above, it is indispensable to properly control the liquid height for countermeasures against damage due to liquid sloshing of oil storage tanks. Thus, specifying velocity response spectrum Sv is important at the natural period of sloshing as understood from Eqn.2. In addition, Sv at a period of second mode is also important for huge oil tanks.
Long-period ground motions are mainly composed of surface waves, and strongly affected by the deep velocity sediment structure between a source region and a site. Since such structural model for a whole of Japan is still

uncertain except limited area, such as Tokyo area, Osaka area, where large cities locate, we cannot use the theoretical or numerical method such as Finite Difference Method. Thus, we employ an empirical method for prediction of long-period ground motions at more than eighty oil industrial complexes located at various sites in Japan.

6.1 Empirical Method for Prediction

Characteristics of long-period ground motions strongly depend on a combination between source and tank site region. Then, we adopted a concept of seismotectonic zoning, in which source characteristics seem to be similar, in order to extract regionality of long-period ground motions at each site, using displacement records of mechanical seismographs operated by Japan Meteorological Agency from 1950 to 1990. Some seismotectonic zoning maps have been proposed in Japan as shown in Fig.4. Since the natural period of seismometer is about 6 sec, the records are pertinent for long-period ground motion prediction. However, they were analogue, and were digitized by means of image processing method. Regionality R(T) of long-period ground motions at a site is defined as follows.

$$R(T) = \sum_{i=1}^{N} Fo(T)i \,/\, Fc(T)i \tag{6.1}$$

Fo(T)i , Fc(T)i, and N are observed Fourier acceleration spectrum, standard spectrum given by Eqns.6.3 - 8 for i-th earthquake derived by Zama (2000), and number of earthquakes in each seismotectonic zone, respectively. Thus, we can easily predict acceleration spectrum Fp(T) in Eqn.6.2, using magnitude (M), epicentral distance (r) of a target earthquake, and α=0.001km^{-1}.

$$Fp(T) = R(T)Fc(T) \tag{6.2}$$

Standard spectrum for earthquakes in a subduction zone:

$$Fc(T) = 4.8 \cdot 10^{0.5\mathrm{M}-1.5} \exp(-\alpha \cdot r)/r^{0.5} \ldots (M \geq 6.9) \tag{6.3}$$

$$Fc(T) = 4.8 \cdot 10^{1.25\mathrm{M}-6.7} \exp(-\alpha \cdot r)/r^{0.5} \ldots (6.2 \leq M \leq 6.9) \tag{6.4}$$

$$Fc(T) = 4.8 \cdot 10^{0.5\mathrm{M}-2.1} \exp(-\alpha \cdot r)/r^{0.5} \ldots (M \leq 6.2) \tag{6.5}$$

Standard spectrum for inland earthquakes:

$$Fc(T) = 4.8 \cdot 10^{0.5\mathrm{M}-2} \exp(-\alpha \cdot r)/r^{0.5} \ldots (M \geq 6.8) \tag{6.6}$$

$$Fc(T) = 4.8 \cdot 10^{0.6\mathrm{M}-2.76} \exp(-\alpha \cdot r)/r^{0.5} \ldots (6.4 \leq M \leq 6.8) \tag{6.7}$$

$$Fc(T) = 4.8 \cdot 10^{0.9\mathrm{M}-4.68} \exp(-\alpha \cdot r)/r^{0.5} \ldots (M \leq 6.4) \tag{6.8}$$

6.2 Validity of Empirical Method

Figure 5 shows the comparison between observed acceleration spectrum and estimated spectrum by Eqn.6.2 in Niigata for the 1993 Hokkaido-nansei Oki earthquake (Mw7.8) as an example of large earthquake in subduction zone, and Figure.6 shows the comparison for the 1930 Kita-Izu earthquake (Mw7.0) as an example of inland earthquake. They are in good agreement with each other. Since some other estimations for large earthquakes also gave good accuracy, it is considered that the empirical method is available for the prediction of spectra of long-period strong ground motions.

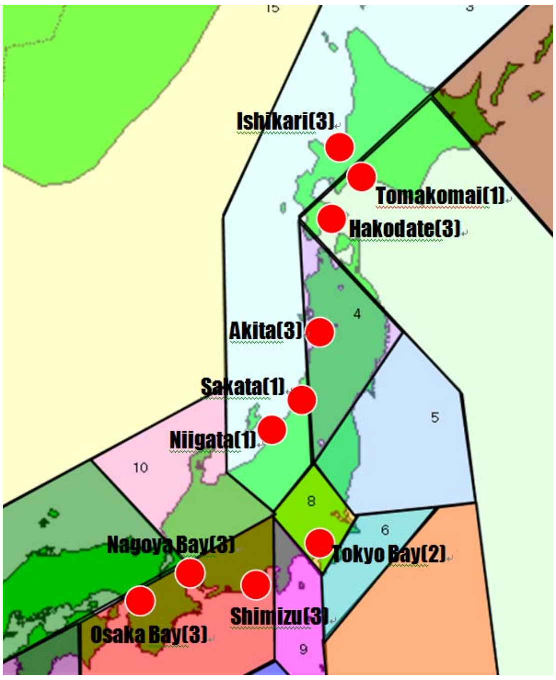
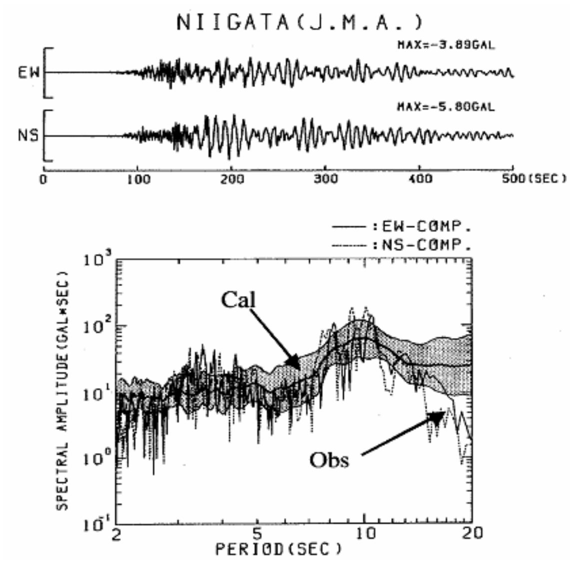


Figure 4 Seismotectonic zoning map by JMA(1990) treated in this study and tank sites corresponding to Region-1 indicated by closed circles



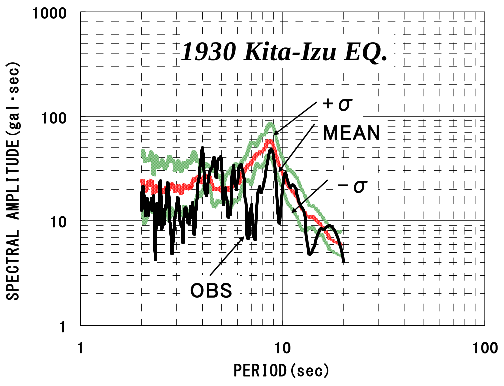


Figure 5 Comparison between observed and calculated spectra at Niigata for the 1993 Hokkaido Nansei-oki earthquake. Shaded area shows predicted spectrum with standard deviation.

Figure 6 Comparison between observed and calculated spectra at Tokyo for the 1930 Kita-Izu earthquake.

6.3 Zoning and Revised Velocity Response Spectra

We estimated Fourier acceleration spectrum Fp(T) for earthquakes with expected maximum magnitude in each seismotectonic zone (Hagiwara, 1991). Here, we regarded Fp(T) as velocity response spectrum Sv in Eqn.2.2, because it was confirmed through many calculations that smoothed Fp(T) is equivalent to Sv with damping factor of 0.5% for liquid sloshing of a single-deck floating roof tank, and also regarded an envelope of superposed predictions as a predicted spectrum at the site.

Based on the observation of damage situation and current regulation in which Sv is about 100cm/s, more than 80 oil industrial complexes in whole of Japan were divided into the following three categories, that is,

Region-1: predicted spectral amplitudes are over 100 cm/s at periods of more than 7 sec.
Region-2: predicted spectral amplitudes are over 100 cm/s at periods of less than 7 sec.
Region-3: predicted spectral amplitudes are below 100 cm/s at the whole period range.

When JMA observatories do not locate near tank sites, records should be newly collected and analyzed, because we found the case that spectrum of long-period ground motion at a tank site considerably differ from the one at an observatory even if the distance is no more several km, as observed at Tomakomai in the 2003 Tokachi-oki earthquake. Then, we collected and analyzed data from strong motion observation networks (K-NET, KiK-net) operated by the National Research Institute for Earth Science and Disaster Prevention and data by Port and Harbor Research Institute near tank sites. Furthermore, some prediction results by the empirical Green function method and numerical method such as FDM were also collected and re-examined. After all, 10 areas including 20 oil industrial complexes are categorized into Region-1 shown as closed circles in Fig.4 and are considered having high potential risk for large liquid sloshing of oil storage tanks.

For practical use, envelopes of predicted spectra in Region-1 were simplified and broken down into three patterns based on their dependency on the period as shown in Fig.7, while existing horizontal design spectrum for liquid sloshing is constant in both period and region. Proposed spectra have 210cm/s in maximum which is equivalent to about 4m of the distance between liquid surface and top angle of a tank.

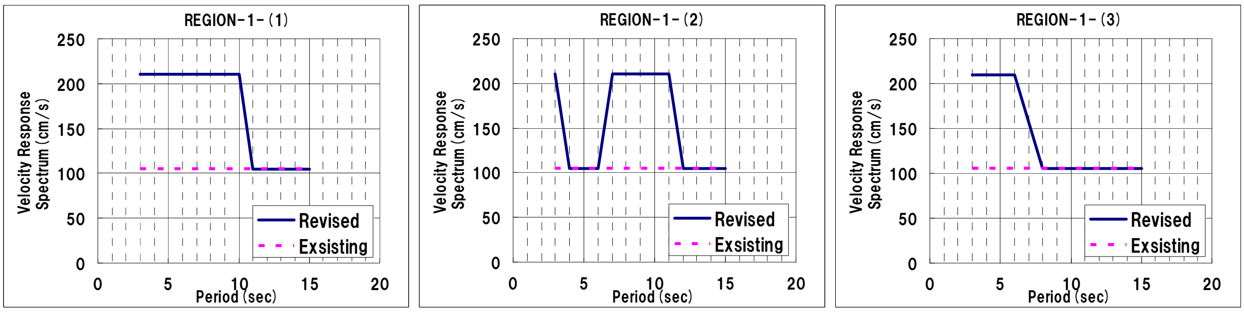


Figure 7 Proposed design velocity response spectra for Tomakomai, Sakata, Niigata (left), for Tokyo bay area (middle), and for Ishikari, Hakodate, Akita, Shimizu, Nagoya Bay area, Osaka Bay area (right)

7. CONCLUDING REMARKS

Yamauchi et al. (2006) proposed a simplified method to evaluate the strength of floating roof considering effects of non-linearity and 2-mode sloshing of liquid in a cylindrical tank based on the detail FEM analysis for damaged tanks at Tomakomai by Miura (2004). On the other hand, Nishi et al. (2008) conducted sloshing experiments by directly vibrating the floating roof of an actual 38-m-diameter tank using air cylinders to examine the damping factor of liquid sloshing with a floating roof, non-linear effects presumed in derivation of the simplified method by Yamauchi et al. (2006), and deformation of the pontoon ring and the behavior of the strain produced at pontoon of the floating roof, and they confirmed the simplified method is adequately applicable to real floating roof tanks. Applying the method to tanks at Tomakomai on basis of the design spectrum, Yamauchi et al. (2006) could elucidate the damage of floating roofs. This means that the strength evaluation of floating roof became possible during liquid sloshing, taking the regionality of long-period ground motion characteristics into consideration. Based on the results, Fire and Disaster Management Agency revised Fire Service Law associated with the horizontal seismic intensity for liquid sloshing shown in Fig.7 and newly added the method to evaluate the strength of floating roof, which were enforced on April 2005, and a certain number of floating roofs are to be reinforced before 2017, if necessary in order to prevent similar damage to large oil storage tanks due to future larger earthquakes such as Tokai earthquake.

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