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REVISION OF DESIGN SPECTRA FOR LIQUID SLOSHING OF OIL STORAGE TANK IN JAPAN

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ABSTRACT

The 2003 Tokachi-oki earthquake (Mw=8.0) caused severe damage to oil storage tanks by liquid sloshing. In particular, at the Idemitsu Refinery at Tomakomai in Hokkaido (northern part of Japan), two tank fires broke out and seven floating roofs sank, where large liquid sloshing more than 3m was excited by the long-period strong ground motions.

According to the Japan Fire Service Law regulating liquid level at that time, the distance (Hc) between liquid surface and top angle is calculated assuming that the velocity response spectrum (Sv) is about 100 cm/s at a period of sloshing, which is roughly equivalent to about 2m of Hc. On the other hand, Sv calculated from records at Tomakomai exceeded about two times as the regulation at periods from about 4 to 8 sec. Thus, it was necessary to revise Sv as a function of period and region.

Prediction of long-period ground motions, which are mainly composed of surface waves, is very difficult because the S-wave velocity structures down to the basement (which strongly affect characteristics of long-period ground motions) have not been clarified in the whole region of Japan. Attention was paid to the seismic records of JMA displacement type strong motion seismographs, which can accurately record long-period ground motions and have been working at 112 observatories from 1950 to1990.

It was suggested from records that the effects of source and path on the ground motion characteristics are almost the same for every earthquake in a seismotectonic zone, and that the empirical prediction seems to be available considering scaling law of fault parameters. The author proposed that the empirical prediction equations be based on recent studies associated with the relations between earthquake magnitude and fault parameters, and developed the database of more than 10,000 components of digitalized records.

Considering both predicted spectra at petroleum industrial complexes for earthquakes with maximum expected magnitude in each seismotectonic zone and damage pattern of oil storage tanks at Tomakomai, the author proposed design spectra for liquid sloshing of oil storage tank in Japan as a function of period and region as shown in Fig. 14. The design spectra were adopted in the revised Japan Fire Service Law enforced on April 2005.

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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 the author 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 earthqauke, seismic design spectra for liquid sloshing of storage tank oil in the Fire Service Law in Japan was revised in order to prevent the damage due to earthquakes in the near future.

Structure of Tank and Liquid Sloshing

Structure

In general, oil storage tanks are classified by the type of roof, such as corn roof tank (CRT), floating roof tank (FRT) and covered floating roof tank (CFRT). Severe damage such as fire and roof sink was seen in single-deck floating roof tanks in the 2003 Tokachi-oki earthquake. Figure 1 shows a typical structure of single-deck FRT. Floating roofs are used in many large-size oil storage tanks to reduce evaporation. A single deck floating roof consists of a thin circular plate (deck) attached at the edge to a buoyant ring (pontoon) of boxed shaped cross section as illustrated in Fig. 2. The pontoon consists of the inner rim, the outer rim, the upper plate and the bottom plate. Each plate is usually single-fillet welded along all of their edges and is required to make each compartment liquid tight. The single deck floating roofs are usually designed to have sufficient buoyancy to remain afloat for the condition that single deck and any two adjacent pontoon compartments are punctured. The space between the outer rim and tank shell is sealed by a flexible device that provides a reasonably close fit to the shell surfaces.

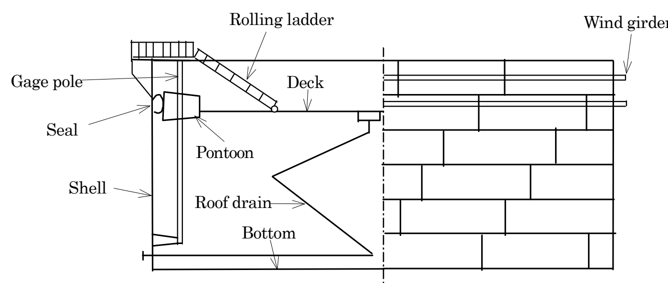

Figure 1. Typical structure of a single-deck floating roof tank.

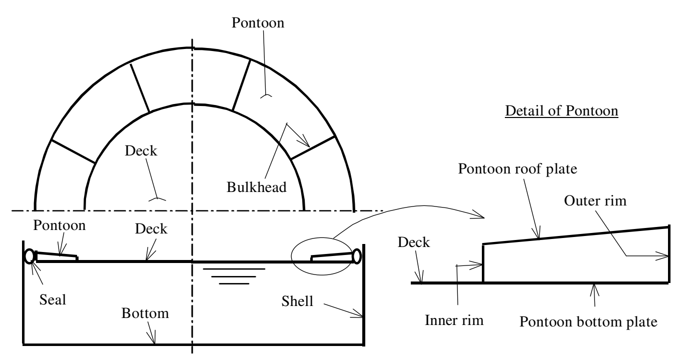

Figure 2. Single-deck floating roof.

Liquid Sloshing

According to the velocity potential theory with rigid tank, the natural period **Ts** of sloshing is given by Eq.1:

$$T_S = 2\pi\sqrt{\frac{D}{2g\varepsilon_1}\coth\left(2\varepsilon_1\frac{H}{D}\right)} \quad (1)$$

where g is the acceleration due to 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:

$$\eta_{\max} = 2.6295 \frac{D}{gT_S} S_V \tag{2}$$

Eq. 2 means that **Sv** is decisively important to estimate liquid sloshing. According to the regulation in Fire Service Law of Japan enforced in 1983, about 2m of maximum liquid height was determined by the velocity response spectrum **Sv** which is assumed constant, that is, about 100 cm/s (damping factor = 0.5%) in the long-period range and in the whole of Japan.

Characteristics 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. Fig. 3 shows the velocity waveforms along the coast from Erimo observatory closest to the epicenter to it 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 the large distance (about 230km) from the epicenter. Furthermore, long-period ground motions predominate and duration time becomes larger. 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 at that time in the period range from 5 to 10 sec. as shown in Fig. 4.

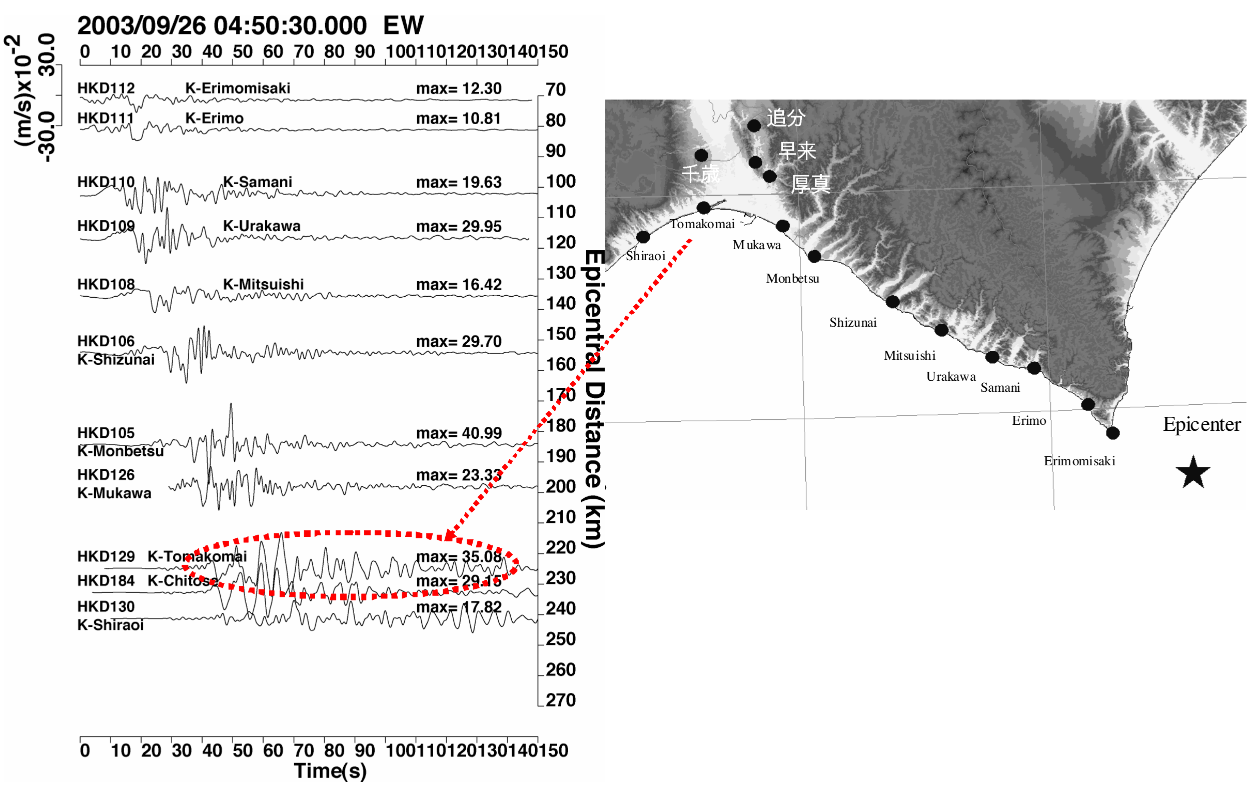

Figure 3. Velocity response spectra at K-net stations in and around Tomakomai.

Heavy Damage of Oil Tank and its Cause

Two tank fires occurred. One broke out during the earthquake as shown in Fig. 5, which shows three fires;

a ring fire between the floating roof and the shell plate, a fire on the ground of tank side, and a fire from a pipe located at the north side of the tank. According to Nishi and Yokomizo (2006), the cause of ring fire is considered as the spark at the collision between the roof and the equipments for support of the guide and the gauge pole above the top angle. Fire on the ground was brought from overflow of the burning oil in the ring fire. The cause of the pipe fire is due to the oil that splashed out of the crack of the pipe due to the earthquake ground motions of at most 70 gals in PGA took fire from overflowed burning oil of the ring fire.

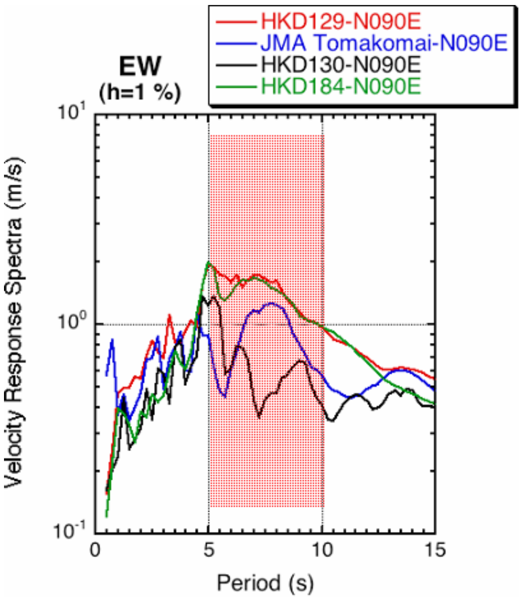

Figure 4. Velocity response spectra at K-net stations in and around Tomakomai.

Figure 5. Tank fire just after the earthquake (photo by Tomakomai Fire Service).

Figure 6. Tank fire occurred two days after the event (photo by Fire and Disaster Management Agency).

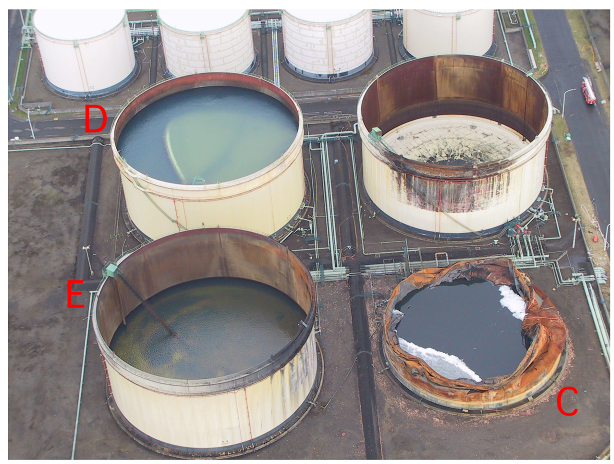

Figure 7. Sunken floating roof (D and E) and pool fire tank (C).

Another fire at the naphtha tank that became a full surface fire occurred two days after the earthquake (Fig. 6) and continued for 44 hours despite the best efforts of the fire brigades. Until fire broke out from the event, fire foam was dropped on the oil surface in order to prevent fire breakout, because the floating roof sank and the naphtha was exposed to the 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).
There were seven tanks of which floating roofs sank as shown in Fig. 7. Furthermore, overflow of oil from some tanks were observed because of large sloshing excited by the unexpected long-period strong ground motions. Large amounts of oil spilt on the floating roof and flew through the drainpipe out of the tank. Another damage due to liquid sloshing such as deformation or failure of gauge pole, guide pole, rolling ladder, roof or its rafter, weather hood, foam dam, and so on were also observed in and around Tomakomai.

Relation between the Maximum Sloshing Wave Height and Damage in Tomakomai

Since there was not much data about maximum sloshing wave height η_{max}, η_{max} was calculated for all tanks in Tomakomai shown in Fig. 8, applying the two dimensional response analysis method (Zama, 1985) assuming appropriate damping for each roof-type tank to seismic records at tank sites after confirming the accuracy through the comparison between estimations and observations. As is obvious, 2D-response analysis is required because of the complex orbit of horizontal ground motions. 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. Severely damaged tanks such as fire and sinking of the 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.

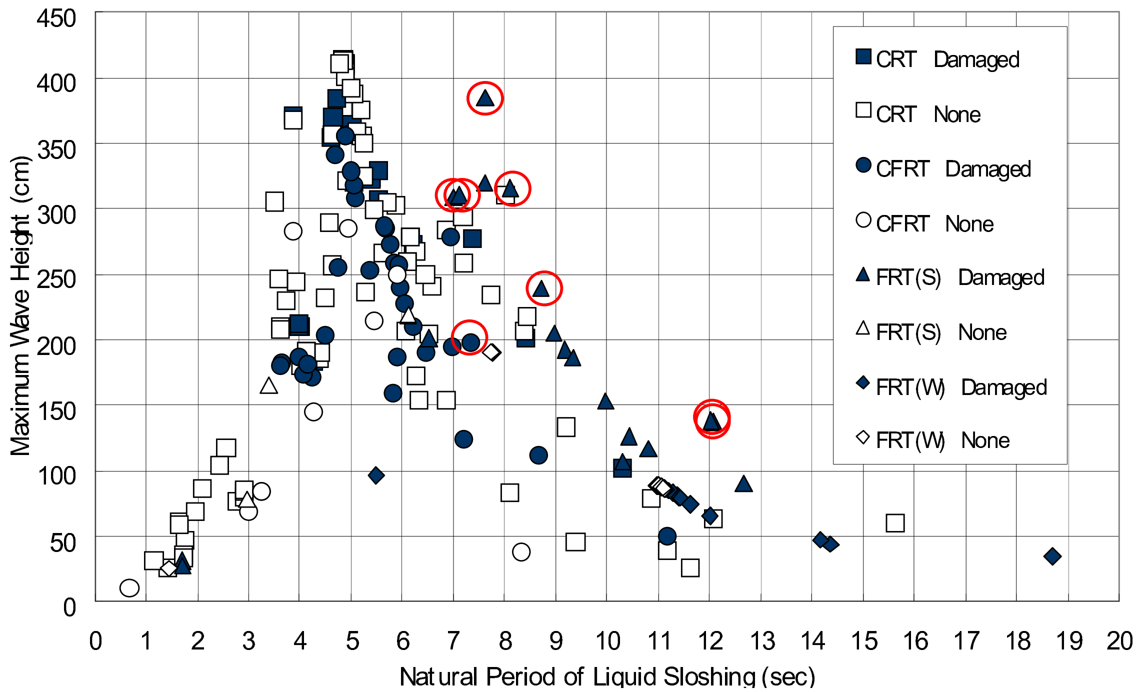

Figure 8. Estimated maximum sloshing wave height at Tomakomai. Shaded symbols show tanks with some damage. Data enclosed by circles indicate tanks with severe damage such as fires, sinking roofs and so on.

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 the time of the earthquake, and the sloshing natural period was T_1=12.0 sec, 2nd mode was T_2=5.5 sec. Fig. 9 shows the damage of the floating roof of this tank. The direction of the main sloshing was roughly presumed to be a direction of EW, and damage with the main buckling deformation was seen in the outer rim and the inner rim of the pontoon located in this direction. Moreover, similar damage was also seen in the pontoon located in orthogonal direction to the main sloshing, NS direction. This floating roof sank several days after the earthquake.

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. 5. 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 9. Failure of pontoon.

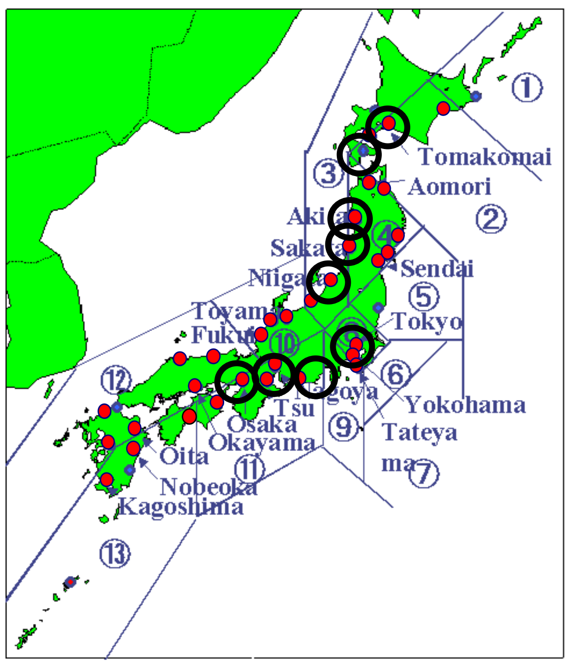

Figure 10. Seismotectonic zoning map by JMA (1990), observatories treated in this report, and Region -1 indicated by large circles.

Specified Seismic Design Spectra for Countermeasure against Liquid Sloshing

Basic Concept

As mentioned above, it is indispensable to properly control the liquid height. Thus, specifying velocity response spectrum **Sv** is important at the natural period of sloshing as understood from Eq. 2. In addition,

Sv at a period of second mode is also important for countermeasures against sloshing of 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 the whole of Japan is still uncertain except in limited areas such as the Tokyo area, Osaka area, where large cities locate, we cannot use the theoretical or numerical method such as Finite Difference Method. Thus, an empirical method for prediction of long-period ground motions at more than eighty oil industrial complexes is employed.

Regionality and Ground Motion 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, where source characteristics seem to be similar, in order to extract regionality in the long-period range at each site using displacement records of mechanical seismograph operated by Japan Meteorological Agency from 1950 to 1990. Some seismotectonic zoning maps have been proposed in Japan as shown in Fig. 10. Since the natural period of seismometer is 6 sec, it is pertinent for long-period ground motion prediction. Records were analogue, and were digitized by means of an image processing method. Regionality **R(T)** in the long-period range at a site is assumed as follows.

$$\mathbf{R(T) = \sum(Fo(T)i / Fc(T)i) / N \quad i = 1, N} \tag{3}$$

Fo(T)i , **Fc(T)i**, and **N** are observed Fourier acceleration spectrum, standard spectrum defined by Eqs. 5 - 10 for i-th earthquake, and number of earthquakes in a seismotectonic zone, respectively. Thus, we can easily predict acceleration spectrum at a site using Eq. 4, magnitude (M) of a target earthquake, epicentral distance **r**, and **R(T)** given by Eq. 3.

$$\mathbf{Fp(T) = R(T)Fc(T)} \tag{4}$$

Standard spectrum was extended by adopting recent studies on the relation between M and source parameters such as seismic moment, fault length, and so on, based on the representation by Kudo (1989), which gave the attenuation curve of acceleration spectrum as a function of both M and r, in the long-period range using the source model of Savage (1989) and normal mode theory.

Standard spectrum for earthquakes in a subduction zone:

$$Fc(T) = 4.8 \cdot 10^{0.5M - 1.5} \exp(-\alpha \cdot r) / r^{0.5} \quad (M>=6.9) \tag{5}$$

$$Fc(T) = 4.8 \cdot 10^{1.25M - 6.7} \exp(-\alpha \cdot r) / r^{0.5} \quad (6.2=<M<6.9) \tag{6}$$

$$Fc(T) = 4.8 \cdot 10^{0.5M - 2.1} \exp(-\alpha \cdot r) / r^{0.5} \quad (M<6.2) \tag{7}$$

Standard spectrum for inland earthquakes:

$$Fc(T) = 4.8 \cdot 10^{0.5M - 2} \exp(-\alpha \cdot r) / r^{0.5} \quad (M>=6.8) \tag{8}$$

$$Fc(T) = 4.8 \cdot 10^{0.6M - 2.76} \exp(-\alpha \cdot r) / r^{0.5} \quad (6.4=<M<6.8) \tag{9}$$

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

where, $\alpha=0.001km^{-1}$.

Regionality and Ground Motion Prediction

Figure 11 shows an example of regionality in Tokyo, Niigata, and Osaka for each source zone (3, 9, and 11 in Fig. 10). For earthquakes in zone 3, ground motions in Niigata at a period of 10 sec will be about three times as strong as in a standard region. As to Tokyo, ground motions from 8 to 9 sec for earthquakes in zone 9 will be shakable more than three times as standard. Thus, we can narrow down source regions and period range to be careful at each observatory from these regionalities.

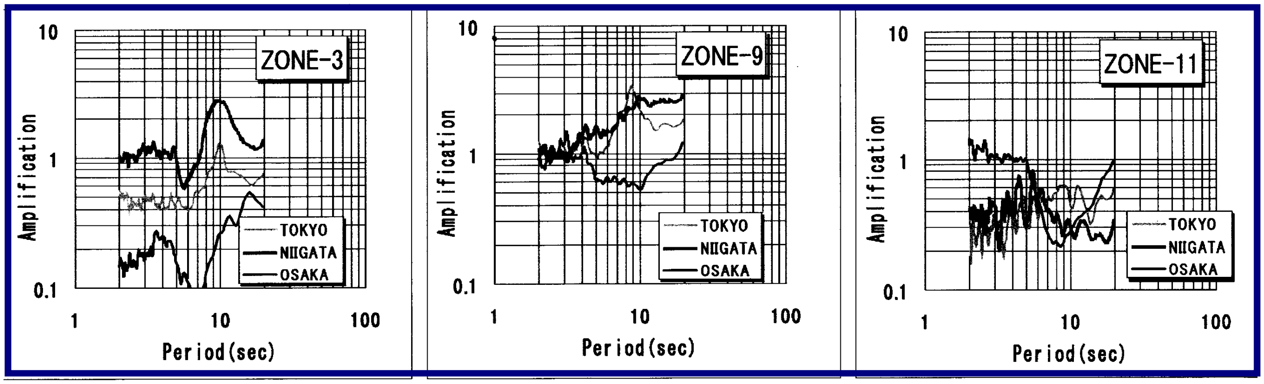

Figure 11. Regionalities at Tokyo, Niigata, and Osaka for zone-3 (left), zone-9 (mid), and zone-11 (right) in Fig. 10, respectively.

Fig. 12 shows the comparison between observed acceleration spectrum and estimated spectrum by Eq. 4 in Niigata for the 1993 Hokkaido-nansei Oki earthquake (Mw7.8) as an example of large earthquake in subduction zone, and Fig. 13 shows the comparison for the 1930 Kita-Izu earthquake (Mw7.0) as an example of an inland earthquake. They are in good agreement with each other. Thus, it is concluded that the empirical method is available for the prediction of spectra of long-period strong ground motions.

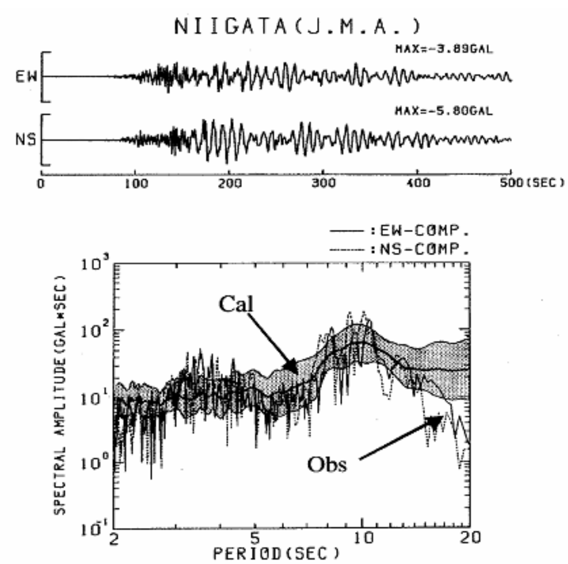

Figure 12. Comparison between observed and calculated spectra at Niigata for the 1993 Hokkaido Nansei-oki earthquake. Shaded area shows predicted spectrum with standard deviation.

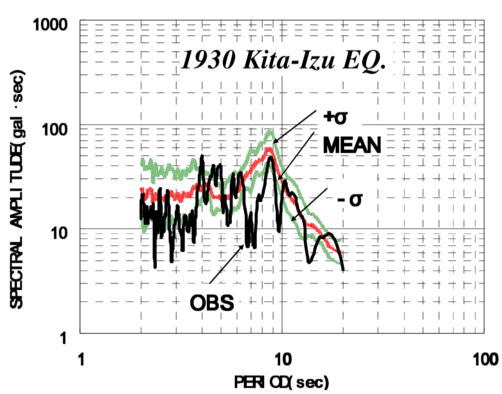

Figure 13. Comparison between observed and calculated spectra at Tokyo for the 1930 Kita-izu earthquake.

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 Eq. 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, more than 80 oil industrial complexes throughout the whole of Japan were divided into the following three categories,

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 are not located near tank sites, records should be newly collected and analyzed, because it was found that characteristics of long-period ground motion at the tank site differ considerably from the 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 the tank sites. Furthermore, some prediction results by the empirical Green function method and numerical method such as FDM (Aichi Pref. 2003; Furumura 2004; Hayakawa and Furumura 2004; Hijikata et al. 2004; Kamae 2004; Nozu 2004, Tsurugi et al. 2005) were also collected and re-examined. Overall, 9 areas including 20 oil industrial complexes are categorized into Region-1 shown as great circles in Fig. 10 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. 14, while existing horizontal design spectrum for liquid sloshing is constant in both period and region. Proposed spectra have a maximum of 210cm/s, which is equivalent to about 4m of the distance between liquid surface and top angle.

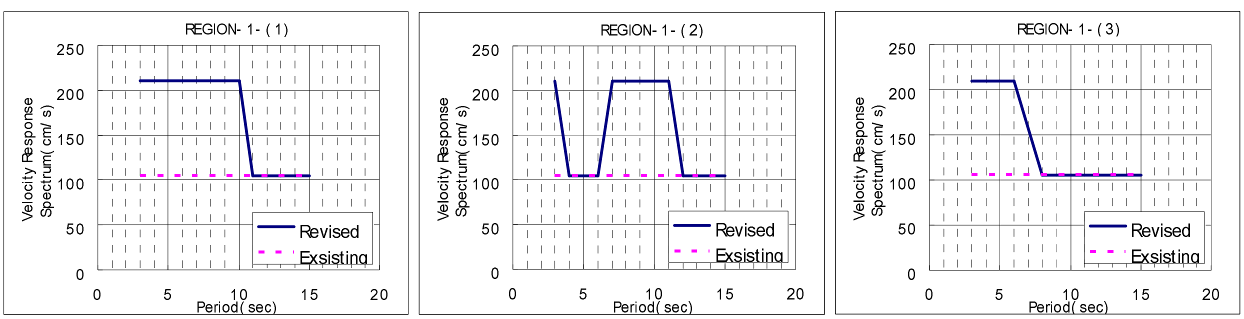

Figure 14. Proposed velocity response spectra for Tomakomai, Sakata, Niigata (right), for Tokyo bay area (middle), and for Hakodate, Akita, Shimizu, Nagoya area, Yokkaichi, Osaka area (left).

Concluding Remarks

Considering the heavy damage to oil storage tanks in the 2003 Tokachi-Oki earthquake, the intensity of long-period ground motions supposed at more than 80 petroleum industrial complexes throughout Japan by large earthquakes in the future has been investigated. Using the proposed empirical prediction equations and data, more than 10,000 components of digitalized records of JMA displacement type seismometers, long–period strong ground motion at tank sites were predicted, and twenty petroleum industrial complexes with higher risk of large sloshing were extracted. Velocity response spectra predicted at these extracted sites were classified into three patterns shown in Fig. 14, and have 210cm/s in maximum which is equivalent to about 4m of the distance between liquid surface and top angle. FDMA amended Fire Service Law associated with the horizontal seismic intensity for liquid sloshing based on the spectra presented in Fig. 14, which were enforced on April 2005. After that, FDMA has implemented the strong motion observations at 9 areas categorized into Region-1 by the velocity type seismometers in order to enhance the accuracy of predicted spectra, experiments on liquid sloshing of large-scale tanks in order to understand sloshing behavior correctly, and investigation of suitable enforcement to pontoons in order to prevent damage of oil storage tanks due to liquid sloshing excited by the long-period strong ground motions, which will be strongly generated from very large earthquakes along the Nankai Trough in the near future.

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