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SEISMIC HAZARD ASSESSMENT FOR LIQUID SLOSHING OF OIL STORAGE TANKS DUE TO LONG-PERIOD STRONG GROUND MOTIONS IN JAPAN

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SUMMARY

Semi-empirical expression for acceleration spectrum of long-period ground motion was revised on the basis of recent studies associated with the relations between earthquake magnitude and fault parameters. It was confirmed that the standard deviation of amplification factor obtained by applying the semi-empirical expression to JMA displacement type strong motion records became smaller and the accuracy of predicted acceleration spectra of large earthquakes was improved compared with the case of the without revision. Consequently, the real-time system for prediction of long-period ground motion has been developed, in order to provide the information for assistance of pertinent emergency responses such as prohibition of the use of the fire just after an earthquake.

On the other hand, the 2003 Tokachi-oki earthquake (M8.0) brought us a chance to revise the regulation on liquid sloshing of oil storage tanks, because long-period strong ground motions observed at Tomakomai, where oil tanks were severely damaged, were nearly twice as strong as the regulation in Japan Fire Service Law. Then, we have been working to set acceleration spectral level in the petroleum terminals and bulk storage facilities using the above-mentioned real-time system for future large earthquakes with shallow focal depths and maximum expected magnitude in the seismotectonic zones

INTRODUCTION

The 2003 Tokachi-oki earthquake (M=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 degree 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. Especially in the Idmitsu Refinery, two fires broke out and six floating roofs sank, and 30 tanks suffered some degree 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.

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Since liquid sloshing of oil storage tank can be treated as an oscillating problem of one mass system with small damping, ground motion plays a deterministically important role in grasping its behavior. Natural period of sloshing depends on the diameter of tank and the liquid height, and it may be about 3 seconds to 15 seconds. Excitation of sloshing is determined by the power of seismic ground motion in this period range.

The characteristic of long-period ground motion differs greatly by the observation location and the location of epicenter. Then, Zama[1-4] tried to extract the regional characteristics of long-period ground motion quantitatively using strong-motion records of Japan Meteorological Agency (JMA) with accuracy in the long-period range and with long observation period (about 40 years).

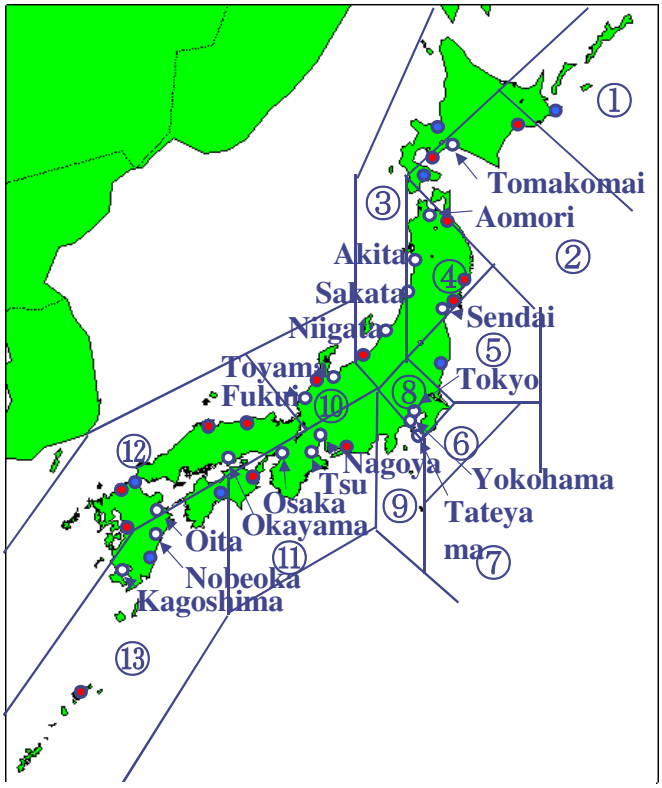

Fig.1 Station location and seismotectonic zoning by JMA[5]

Excitation of liquid sloshing has seldom correlation with the seismic intensity because of the difference of frequency characteristic. Thus, the occurrence of terrible liquid sloshing during no felt earthquake may bring the delay of emergency responses for sloshing of liquid, especially oil tank fires. In this paper, firstly we show a new spectrum model used as a standard model to calculate the above-mentioned regional characteristic and verify its validity. Secondary, we report on a long-period strong ground motion prediction system, with which it becomes possible to grasp the danger of sloshing immediately after an earthquake. Finally, we propose the revised spectral level in the long period range for most petroleum industrial complex areas in Japan, in consideration of sever damage of oil storage tanks at Tomakomai due to the 2003 Tokchi-oki earthquake based on the prediction results by the above-mentioned prediction system.

DATA

After the 1995 Kobe earthquake, many strong-motion seismographs such as K-net have been installed in Japan. Since they are accelerometers, the record duration is about 1 minute in most cases, which is inadequate for the analysis of long-period ground motions mainly composed of surface waves. Therefore, attention is paid to the records of JMA displacement type strong motion seismometer (DSM) that has the natural period of 5 to 6 seconds. Since the DSM has about 40 years' observation period from 1950 and has been installed in many JMA observatories, it is very suitable for investigating the regional characteristic of long-period ground motion in the whole country.

Figure 1 shows the classification of seismic source zone by JMA[5] and 33 stations in areas close to the oil industrial complexes. We collected earthquake records by coping original records and/or printing microfilms with the same sizes, which have the maximum amplitude of displacement of more than 1mm, for earthquakes with magnitude (M) of more than 6.0 and the focal depth of less than 60km. Although the natural period of DSM is about 6 seconds, the recorded amplitude at a period of 10 seconds attenuates to one third due to the frequency characteristic of the DSM. Thus, the instrumental correction is needed for

evaluating a real ground motion. We used a system that can digitize waveform semi-automatically from image data of earthquake records taken in a personal computer by an image scanner (Zama[8]).

PREDICTION METHOD

Frame

Sloshing wave height (Wh) can be evaluated by the following equation.

$$Wh = D / 2g \cdot 0.837 (2\pi / Ts) \cdot Sv \qquad (1)$$

where, g and Sv are gravity acceleration and velocity response spectrum which could be regarded as acceleration Fourier spectrum because of small damping. As mentioned above, characteristics of the long-period strong ground motion differ considerably from both observatory and seismic source zone (ZONE). This difference is taken as the regional characteristic and can be extracted by comparison between the observed and the standard spectrum that is an average seismic source and propagation characteristics. If a certain ZONE is taken as seismotectonic zone and the scaling law of seismic source spectrum is set up appropriately, it is expected that regional characteristic acquired from each earthquake in the same zone will almost be the same, because the propagation characteristic will be almost the same for a certain specific location. Accordingly, it becomes possible to predict the ground motion in form of a spectrum due to any earthquakes in the ZONE by using the regional characteristic. Thus, we target at the acceleration Fourier spectrum obtained in process of the instrumental correction

Derivation of Standard Spectral Model

Long-period strong ground motions in the period range of 2 to 20 seconds mainly consist of surface waves. To make it simple, theoretical spectrum of Love wave is considered here. If the seismic source model of Savege[7] is assumed and the normal mode theory is used, the theoretical acceleration spectrum $Fc(\omega)$of Love wave is

$$Fc(\omega) = Mo\, G(\omega) F(\omega)\ \omega^3 I(\omega) / (2\pi r)^{0.5} \qquad (2)$$

Where ω, r, Mo are angular frequency, epicentral distance, and an earthquake moment. $G(\omega)$, $F(\omega)$, $I(\omega)$ is source time function, directivity function, and the excitation function of a surface wave, and they are given respectively as follows.

When taking τ as the rise time, the source time function g(t) is

$$g(t) = 1 - \exp(-t / \tau) \qquad (3)$$

and, its Fourier transform is given by

$$G(\omega) = 1 / \omega (1 + \omega^2 \tau^2)^{0.5} \qquad (4)$$

For the unilateral rupture, the directive function $F(\omega)$ is given by

$$F(\omega) = \sin(\omega \xi / 2) / (\omega \xi / 2) \qquad (5)$$

$$\xi = L (\beta / c - \cos\theta) / \beta \qquad (6)$$

where L, β, c, θ is fault length, S wave velocity of a medium, rupture velocity, and the angle between rupture propagating direction and an observation location. When we assume the standard subsurface structure of Japan and 10km of focal depth, I(ω) will be approximately given by $10^{-20.5}$ ($cm^{1/2}$ sec/dyne). When θ is 90 degrees and ω is large, the following expression is given.

$$Fc(\omega)=4MocI(\omega)/(\tau L(2\pi r)^{0.5}) \quad (7)$$

In the short period range than Tc given by (7), it becomes constant. While in the longer period range, it will be attenuated in proportion to the 2nd power of the period. The period of the intersection of two asymptotes is called cut-off period (Tc) that has a relation as

$$Tc = 2\pi\tau \quad (8)$$

As mentioned above, theoretical acceleration spectrum can be calculated if Mo, c, τ, L, and r are given. Kudo[8] gave a semi-empirical expression to the acceleration spectrum (the old model) of a long period earthquake motion as a function of period T by using the empirical relations between M and these values for T $\leqq$ Tc,

$$Fc(T)=4.8\cdot 10^{0.5M-2}\exp(-\alpha(T)\cdot r)/r^{0.5} \quad (9)$$
$$\log\alpha(T)=9.11/T-4.26 \quad (10)$$

where, it is assumed that c = 3km/s, and

$$\log Mo = 1.5M + 16 \quad (11)$$
$$\log\tau = 0.5M - 3.2 \quad (12)$$
$$\log L = 0.5M - 1.8 \quad (13)$$

in the period longer than Tc,

$$Fc(T)=4.8\cdot 10^{0.5M-2}\exp(-\alpha(T)\cdot r)/r^{0.5}\cdot(Tc/T)^2 \quad (14)$$
$$\log Tc = 0.5M - 2.42 \quad (15)$$

Takemura[9] showed that the following relations between Mo and M give better correlation than (11).

$$\log Mo = 1.5M + 16.5 \quad (M\geqq 6.9) \quad (16)$$
$$\log Mo = 2.25M + 11.3 \quad (6.9 > M\geqq 6.2) \quad (17)$$
$$\log Mo = 1.5M + 15.9 \quad (6.2 > M) \quad (18)$$

This is applicable to earthquakes in the subduction zone including the east margin of the Japan Sea. Sato[10] also gave the following relations, as to an interplate earthquake.

$$\log\tau = 0.5M - 3.3 \quad (19)$$
$$\log L = 0.5M - 1.88 \quad (20)$$

These are almost same as (12) and (13). Tc is given as follows from (8).

$$\log Tc = 0.5M - 2.5 \quad (21)$$

It is almost same as (15). Therefore, the difference in the relation of M-Mo contributes to the difference from the old standard model. On the other hand, Takemura[9, 11] derived the relations of M-Mo and M-L for an inland earthquake as follows.

$$\log Mo = 1.2M + 17.7 \quad (22)$$
$$\log L = 0.6M - 2.9 \quad (M \geqq 6.8) \quad (23)$$
$$\log L = 0.4M - 1.38 \quad (M<6.8) \quad (24)$$

If the relation of M- τ is given by (19),

$$Fc(T) \propto 10^{0.07M} \quad (M \geqq 6.8) \quad (25)$$
$$Fc(T) \propto 10^{0.27M} \quad (M<6.8) \quad (26)$$

This means that the ratio of Fc(T) for earthquakes of M7 and M8 is merely 1.7. It is not natural. Accordingly, we derived the relation between M and the average slip velocity (D / τ) from the list of dislocation parameters compiled by Sato[10] as shown in Fig.2. When only paying attention to the inland earthquake of M> 5.0, the following expression is obtained.

$$\log D / \tau = 0.5M - 1.6 \quad (27)$$

When combining (27) to relations of M-D (Takemura[11]), the followings are given in case of M>=6.8.

$$\log D = 0.6M - 1.92 \quad (28)$$
$$\log \tau = 0.1M - 0.32 \quad (29)$$

while M<6.8, it becomes

$$\log D = 0.4M - 0.84 \quad (30)$$
$$\log \tau = -0.1M + 0.76 \quad (31)$$

This leads to $Fc(T) \propto 10^{0.5M}$ when M>=6.8, which is the same with (9).

However, the expression of relations between M and L shown by (23) and (24) gives the discontinuity at M = 6.8. This situation can be also seen in equations of (28) - (31). This is a result obtained from the scaling law of $Mo \propto L^2$ when $Mo>7.5x10^{25}$ dyne-cm and of $Mo \propto L^3$ when $Mo<7.5x10^{25}$ dyne-cm. It has been pointed out that the discontinuity is caused by the appearance of an earthquake fault on the surface around M6.8 (Shimazaki[12]). Since the difference between (23) and (24) at M6.8 is corresponding to 7 km discontinuity of fault length, which causes large fluctuation in evaluating amplification factor described later, it is desirable to avoid the discontinuity. For convenience, the value of L at M=6.8 in (23) was connected to (24) as it was. That is

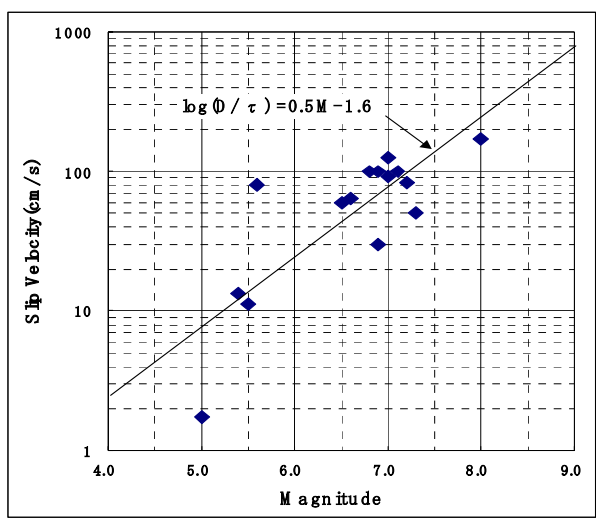

Fig.2 Relation between slip velocity and earthquake magnitude for inland earthquakes in Japan

$\log L = 0.6M - 2.9$ ($M \geqq 6.8$) (23)
$\log L = 1.18$ ($6.4 \leqq M < 6.8$) (32)
$\log L = 0.4M - 1.38$ ($M < 6.4$) (33)

Since the relation of M-τ is also discontinuous at M = 6.8, the followings are given when the intervals of M are taken equally as (22) and (31)-(32).

$\log \tau = 0.1M - 0.32$ ($M \geqq 6.8$) (29)
$\log \tau = 0.6M - 3.72$ ($6.4 \leqq M < 6.8$) (34)
$\log \tau = -0.1M + 0.76$ ($M < 6.4$) (35)

The relation of M-Tc is given using (8) as the follows.

$\log Tc = 0.1M + 0.48$ ($M \geqq 6.8$) (36)
$\log Tc = 0.6M - 2.92$ ($6.4 \leqq M < 6.8$) (37)
$\log Tc = -0.1M + 1.56$ ($M < 6.4$) (38)

Coefficient of M in (35) or (38) is negative. This is contrary to a common sense in seismology that τ will become larger as M becomes larger. It is resulted from the fact that quite large variation of data has been used in Fig.2 based on the derivation of the relation of M-τ. Although a detailed study is needed, equation (35) is used hereafter, because there is not so large change in an absolute value even if M changes from 6.0 to 6.4.

Based on the result that characteristic of long-period strong ground motion in Tomakomai area is mainly controlled by input wave-filed rather than by underground structure (Zama[3]), the apparent relation of Tc-M can be derived from the observed spectra from earthquakes in the Pacific Ocean off northeast Japan as below.

$\log Tc = 0.046M + 0.561$ (39)

The coefficient of M is near to that for inland earthquakes, and differs greatly from that of an interplate earthquake. Essentially, Tc should not be evaluated for the observed spectrum that contains the influence of a propagation path, but for the seismic source spectrum. Tc in (39) is only an apparent value and is not related with the rise time τ. Here, equation (39) is considered as correct regardless of an inland or an interplate earthquake, and is used in derivation of the standard spectrum.

In summary, the standard spectrum for an earthquake in the subduction zone can be given as the follows in case of $T \leqq Tc$,

$Fc(T) = 4.8 \cdot 10^{0.5M-1.5} \exp(-\alpha(T) \cdot r)/r^{0.5}$ ($M \geqq 6.9$) (40)
$Fc(T) = 4.8 \cdot 10^{1.25M-6.7} \exp(-\alpha(T) \cdot r)/r^{0.5}$ ($6.2 \leqq M < 6.9$) (41)
$Fc(T) = 4.8 \cdot 10^{0.5M-2.1} \exp(-\alpha(T) \cdot r)/r^{0.5}$ ($M < 6.2$) (42)

For an inland earthquake, it can be summarized as the follows.

$Fc(T) = 4.8 \cdot 10^{0.5M-2} \exp(-\alpha(T) \cdot r)/r^{0.5}$ ($M \geqq 6.8$) (43)
$Fc(T) = 4.8 \cdot 10^{0.6M-2.76} \exp(-\alpha(T) \cdot r)/r^{0.5}$ ($6.4 \leqq M < 6.8$) (44)

$$Fc(T)=4.8\cdot 10^{0.9M-4.68}\ \exp(-\alpha(T)\cdot r)/r^{0.5} \qquad (M<6.4) \qquad (45)$$

As to the attenuation coefficient $\alpha(T)$, $0.001km^{-1}$ was used as an average value irrespective of the period (Kudo[8]).

Regional Characteristic and Prediction of Ground Motion

Here, we investigate the prediction of long-period strong ground motion based on both the standard spectrum model Fc(T) in the above section and observed records. We define the regional characteristic R(T) for earthquakes in a certain seismotectonic zone (Hagiwara[13]) as the averaged ratio of the observed spectrum Fo(T) to the standard spectrum Fc (T).

$$R(T) = \Sigma\,(Fo(T)i\ /\ Fc(T)i)\ /\ N \qquad i = 1,\ N \qquad (46)$$

where, N is the numbers of earthquake in a certain ZONE. Although the spectral ratio for each earthquake differs with each other, the averaged spectral ration R(T) has a certain tendency. We call R(T) "regionality" or "amplification factor". Acceleration spectrum can be predicted only by giving M and r of a scenario earthquake, using amplification factor evaluated by (46). Namely, the prediction spectrum Fp(T) can be given by R(T) to the zone where the scenario earthquake is located and the standard spectrum Fc(T; M, r).

$$Fp(T) = R(T)Fc(T;\ M,\ r) \qquad (47)$$

As for a seismotectonic zone, we used the classification of seismic source zone by JMA[5] as shown in Fig.1. Moreover, we built the database concerning the digitized records and their spectra and so on for 33 JMA stations. Verification of the prediction accuracy was conducted for large earthquakes in the subduction zone and for inland earthquakes.

Figure 3 shows the comparison of the predicted and the observed spectrum at Niigata for the 1993 Hokkaido-nansei-oki earthquake (M7.8), as an example of an earthquake in the subduction zone. Records from this earthquake are not included in the database. The predicted spectrum explains well the observed spectrum.

Next, the 1930 Kita-Izu earthquake was taken up as an example of an inland earthquake, because predominant long-period strong ground motions due to earthquakes in and around Izu Peninsula in ZONE-9 of Fig.1 has been very often observed in the Kanto Plain (Zama[14]) and M7.3 of this earthquake is the maximum expected magnitude. Figure 4 shows the comparison between the calculated and the observed spectrum from the waveform digitized by Tanaka[15] and both agree with each other mostly. Although both the peaks at periods of about 4 and 5 seconds and the spectral hole near 7 seconds in the observed spectrum cannot be seen in the predicted spectrum. This disagreement could be due to low-precision record as described in Tanaka[15].

In addition to these earthquakes, similar investigations were conducted for several large earthquakes such as the 1978 Miyagi earthquake (interplate), the 1995 Hyogo southern earthquake (inland) and so on, and good results have been obtained. Therefore we concluded that the empirical method is useful for the long-period ground motion prediction.

REAL-TIME PREDICTION SYSTEM

In order to make rapid emergency response against the tank damage by liquid sloshing, we constructed a system that can quickly predict acceleration spectrum using above-mentioned database. The system was

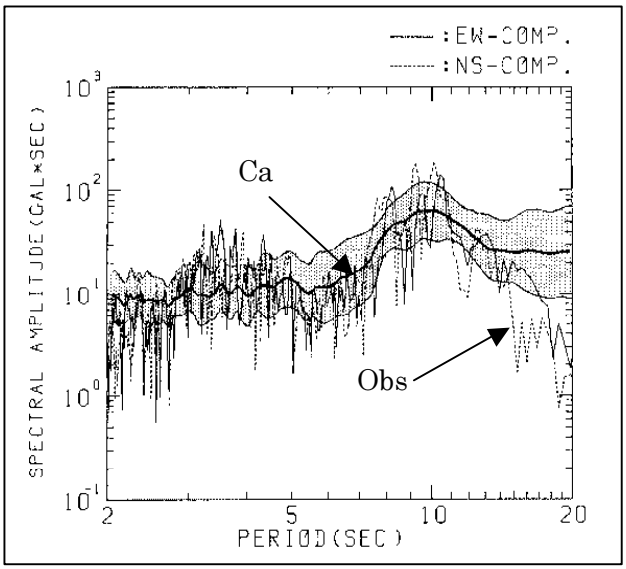

Fig.3 Comparison between calculated and observed acceleration spectra for the 1993 Hokkaido Nansei-oki earthquake at Niigata

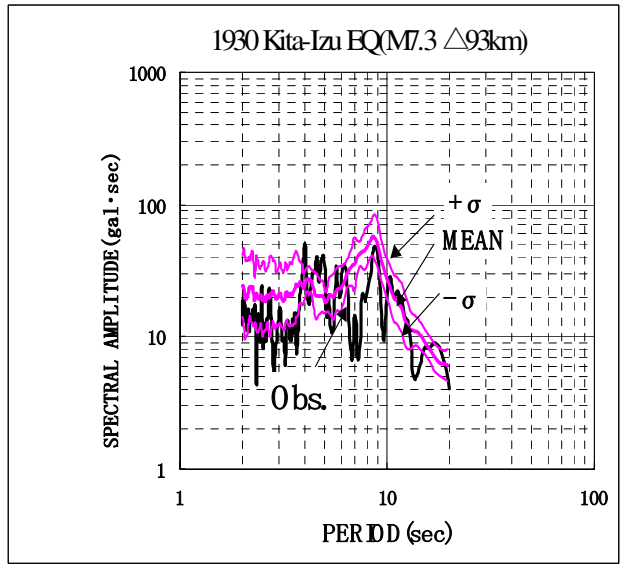

Fig.4 Comparison between calculated and observed acceleration spectra for the 1930 Kita-Izu earthquake at Tokyo

built on top of Microsoft Excel and the main calculation portions were executed by Visual Basic for the diffusion of the system. The processing flow is as follows.

(1) Input coordinates of epicenter and earthquake magnitude (Fig.5a)

(2) Search classification of seismic source zone (ZONE) from the coordinates (Fig.5b)

(3) Extract the regionality R(T) corresponding to the ZONE.

(4) Applying equation (46) to calculate spectrum at each place.

(5) Show the results by graphs. (Fig.5c)

The potential danger by sloshing may be judged by whether the spectrum value exceeds 100 gal*sec or not at the natural period of liquid sloshing, because this value is almost equal to the regulation of Fire Service Law that has defined the space margin height from oil surface to the top angle of the shell plate. Since the natural period (Ts) of liquid sloshing can be easily calculated by both the tank diameter (D) and the height of liquid, sloshing wave height (Wh) can be evaluated immediately using equation (1) when liquid level is monitored just before an earthquake.

ACTIVITY BASED ON TANK DAMAGE BY THE 2003 TOKACHI-OKI EARTHQUAKE

In the regulation, Sv in (1) is about 100cm/sec regardless of both period and region. Fire and Disaster Management Agency made policy to revise Sv in the equation (1) in consideration of severe damage of oil storage tanks in Tomakomai due to the 2003 Tokchi-oki earthquake, based on the prediction results by the above-mentioned prediction system. Prediction has been executed for the earthquakes with maximum expected magnitude in all ZONE shown in Fig.1. Since this prediction depends on records, other methods such as numerical method, earthquake observation and so on, are needed to predict at an arbitrary point. This is an issue in the future.

The fact that floating roofs sank is very serious, because such situation will lead to full-surface tank fire with high possibility. Furthermore, the Headquarters for Earthquake Research Promotion[16] pointed out that large earthquake like the Tokachi-oki earthquake will occur in the near future. Therefore, it is very important and urgent to enforce the strength of floating roof. For that purpose, it is needed to clarify

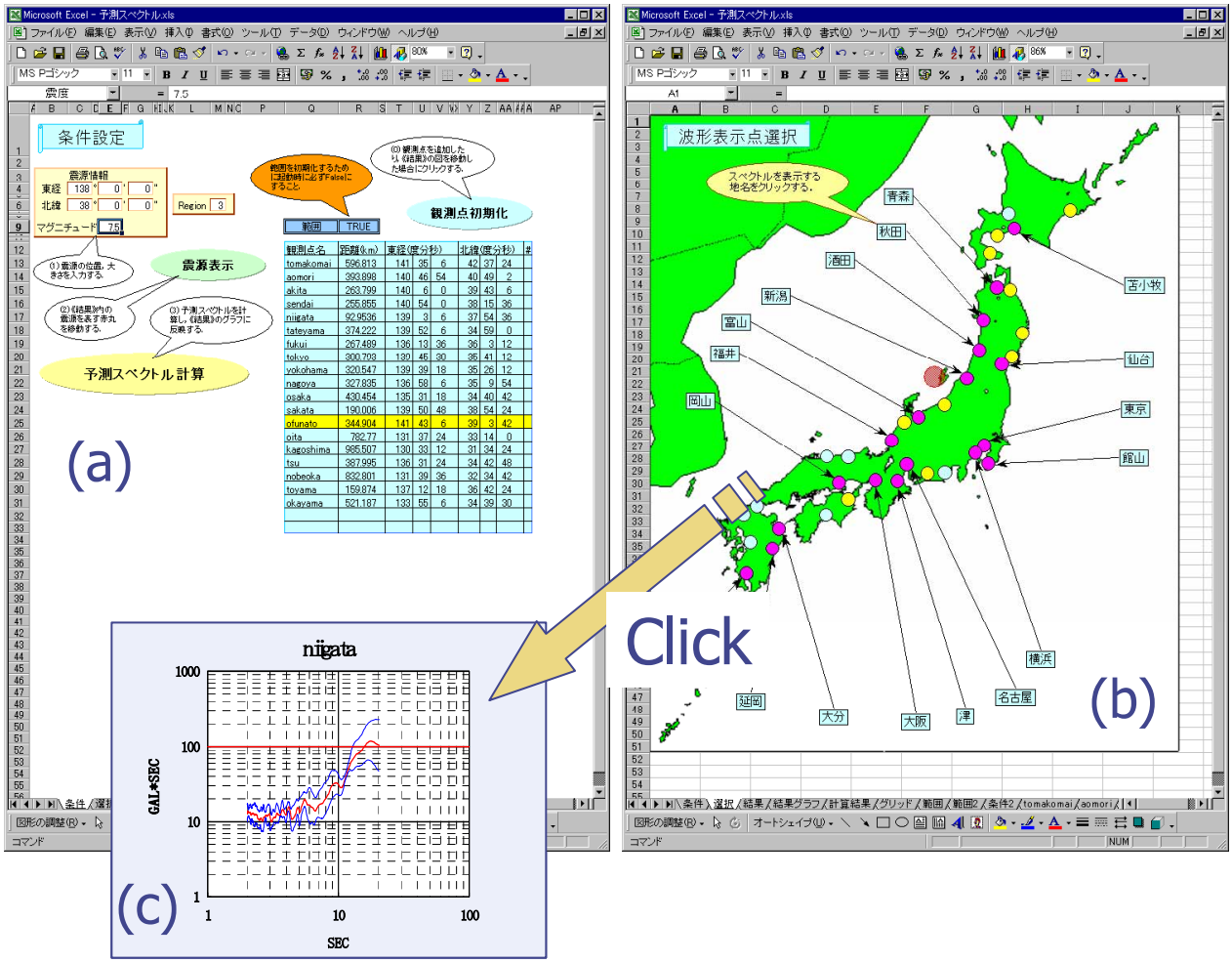

Fig.5 Real-time estimation system for long-period strong ground motion
(a) input form (b) location of epicenter and stations (c) estimated spectrum

where and how force was loaded by liquid sloshing on the basis of the detail investigation of sinking roofs.

CONCLUSIONS

There is almost no correlation between sloshing and the seismic intensity. This shows that even in cases that earthquakes are hardly felt, large liquid sloshing of oil storage tank may still occur and bring about delay of emergency response. Based on this recognition, we developed a system to estimate long-period ground motion, which is crucially important for prediction of sloshing.

Since characteristic of the long-period strong ground motion differs greatly with the seismic source zone and observation site, regionality has been grasped by an empirical method that regards the difference as a deviation of the observed spectrum from a standard spectrum model. Observed spectra have been obtained from displacement strong motion records at JMA stations close to oil industrial complexes because of the frequency characteristic of the seismometer and the observation term

A standard spectrum model was given based on the latest knowledge concerning to the relations between M and fault parameters such as seismic moment and fault length. Then the regionality was evaluated and database was built. Observed spectra were compared with predicted spectra for large several earthquakes. Since results showed that the predicted values can explain well the observed ones, the validity of the empirical prediction method was verified.

Then, a system that can predict the spectrum of long-period strong ground motion easily has been developed on Microsoft Excel. It becomes possible to evaluate sloshing risk of oil storage tank immediately after earthquake. Using the system, we have reexamined Sv in (1) considering the severe damage of oil storage tanks due to the Tokachi earthquake. However, characteristics of the long-period strong ground motion may differ considerably, e.g., there may have 2 times difference in response spectrum even if in a limited area such as Tokyo Bay. Thus, it is necessary to identify the difference of ground motion between the JMA station and the oil storage tank site. In order to do that, it is desired to conduct earthquake observation and accumulate data. It was found from this study that it is possible to predict the acceleration spectrum of large earthquake of M7 - 8 in considerable accuracy, if some earthquake records of M6 class are obtained. Considering the occurrence frequency of earthquake of M6 class in Japan, building database for oil industrial complexes will not be so much difficult.

Recently, the deep underground structure of a wide area has been modeled and the calculation of long-period wave-field has been performed with the finite difference method and so on (Graves[17]). However, there is still very limited information about underground structures and seismic source characteristics. Hereafter modeling and evaluation for subsurface structure and seismic source will be needed. In this process, the consistency should be confirmed between the calculated ground motions and the ones by the empirical method. It will lead the possibility of the prediction with high accuracy for an arbitrary site by numerical method or theoretical method (Zama[18]).

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