Development and verification of tank damage evaluation system using Earthquake Early Warning information

Naoto OHBO
Association for the Development of Earthquake Prediction, Japan

Shinsaku ZAMA
National Research Institute of Fire and Disaster, Fire and Disaster Management Agency, Japan

Tomohiko TSUCHIDA
Japan oil, gas and Metals National Corporation, Japan

Fumitoshi TAKADA
Eisinsystem Co. Ltd, Japan

SUMMARY:
We have developed a system that can estimate tank damage (for example, overflow of liquid, damage of roof and tank) before arrival of seismic waves using the Earthquake Early Warning information (EEW), and can inform the results to users. The verification of the system was conducted through the comparison between the calculated sloshing height by the system using EEW during the 2011 off the Pacific coast of Tohoku Earthquake and the computed sloshing height using observed seismic waves at Oga, Rokkasho, and Ooita sites. At a petrochemical complex in Ooita which locates about 1100km from the epicenter, the computed sloshing heights by the system using both the magnitude of M=8.1 given in EEW and the finally decided magnitude of M=9.0 were 8 cm and 22 cm, respectively. The sloshing height computed using observed seismic waves was 11cm. The evaluated results were in good agreement with the observed one in Ooita, and the validity of system was confirmed.

Keywords: EEW, Long Period Ground Motion, Large Scale Tank, Sloshing, Disaster Prevention System

1. INTRODUCTION

During the 2011 off the Pacific coast of Tohoku Earthquake (Mw=9.0) occurred on March 11, 2011, tsunami and liquefaction caused severe damage to civil structures and buildings. Tank damage due to liquid sloshing was observed at the site that is located about 350km from the epicenter. There was no fire caused by sloshing excited by long-period ground motion, although two big tank fires occurred during Tokachi-Oki-Earthquake (Mw=8.0) in 2003.

As for the damage of tank, fire due to sloshing during Niigata Earthquake (M=7.5) in 1964, failure of bottom plate during Miyagiken-Oki Earthquake (M=7.5) in 1978, fire, overflow of oil and roof damage induced by sloshing during Nihonkai-Chubu Earthquake (M=7.7) in 1983, buckling of shell plate of tank during Sanriku-Haruka-Oki Earthquake (M=7.6) in 1994, and buckling and inclination of small tank during Hyogoken-Nanbu Earthquake (M=7.3) in 1995 have been reported.

Considering the tank site condition (coastal area and reclamation), the most possible damage causes could be summarized as follows: strong ground motion, liquefaction, long-period ground motion and tsunami. Short-period components of seismic ground motion induce coupled motion of liquid and container, and the container would be subjected to both inertia force and dynamic liquid pressure, which causes tilting, sliding and container damage due to insufficient strength. For the damage prevention and mitigation of earthquake risk for the region, and for an efficient patrol to prevent and/or minimize secondary disaster such as fire breakout, diffusion of oil at the tank sites just after an earthquake where tanks are located, a real-time comprehensive damage evaluation system is very useful.

Aiming at disaster prevention and mitigation at a tank yard, the authors have been operating an evaluation system that can predict the sloshing height due to long-period ground motion before the arrival of seismic waves, and accurately evaluate the sloshing height using the arrived long-period seismic waves (Ohbo 2005, Iwahara 2008). In this system, the earthquake information, which is distributed through EEW by the Japan Meteorological Agency (JMA), and the observed seismic records are employed to calculate the sloshing height, based on which the inspection priority of tanks is displayed and transferred to operators and relevant authorities who can judge tanks to preferential inspected. In addition, the prediction function of roof damage due to sloshing and evaluation function of bucking shell plate due to short-period ground motion have been implemented (Ohbo 2010), and the system for oil-storage tanks has been established to predict various kinds of seismic damage (Ohbo 2011).

In this paper, the outline of tank damage in the 2011 off the Pacific coast of Tohoku Earthquake is firstly introduced, and the computed sloshing height using K-NET data nearby the damaged tank is compared with the observed one. Secondly, the problem in use of K-NET data is discussed. Then the outline of the system is introduced, and the comparison between the evaluated sloshing height using EEW during the 2011 off the Pacific coast of Tohoku Earthquake, and K-NET data and the observed sloshing height are conducted. Finally the validity of the system is discussed including estimation of the response spectrum and important points in use of spectrum evaluation formula when applying the system at a different site and the parts to be improved are clarified.

2. TANK DAMAGE AND SLOSHING IN THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

2.1. Tank damage

Figure 2.1 indicates the location of the epicenter of the 2011 off the Pacific coast of Tohoku Earthquake and the tank damage investigation sites along pacific ocean in Tohoku-region (Area-A), along pacific ocean in Fukushima-Ibaraki region (Area-B), Tokyo bay (Area-C), and the site along Nihon-Kai (Area-D). The colour shows the level of the peak ground motion (PGA) (NIED 2011).

Base on the investigations by the NRIFD (Zama, 2012), Table 2.1 shows the damage outline and damage features in Area-A and Area-B corresponding to tsunami, long-period ground motion and short-period ground motion. In Area-A, the movement and failure of tank, oil retaining walls and pipes due to tsunami were observed. In Area-B, liquefaction caused severe damage to tanks and oil retaining walls, and the damage induced by tsunami could only be observed in the area near coastal revetment.

Table 2.2 shows the damage features due to long-period ground motion and the damage outline of floating roof and inner float. In Area-C, 14 of floating roof damage and inner floating damage were confirmed, and shrinking of a floating roof was observed. In Area-D, severe damage of an inner floating

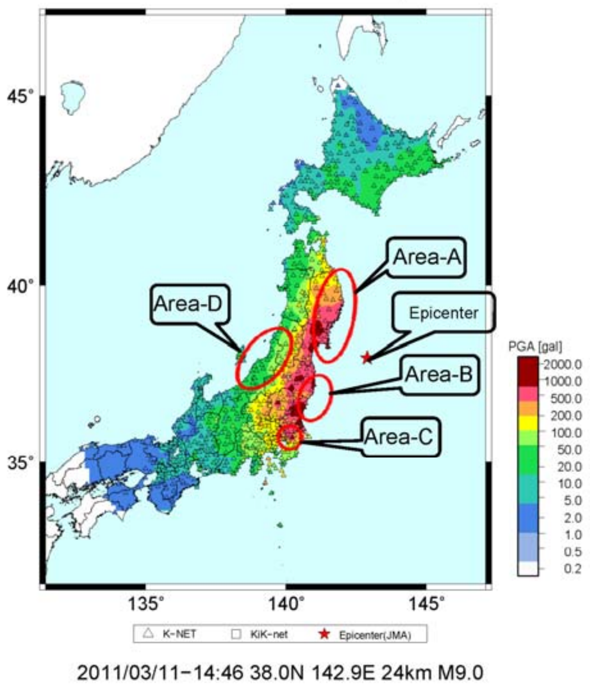


Figure 2.1 damage investigation area and an epicentre (corrected NIED, 2011)

aluminium cover was confirmed (KHK 2011).

2.2. Characteristics of seismic ground motion in the region of damaged tanks

In Area-A, Area-B and Area-C, tank damage due to long-period and short-period ground motions were confirmed. In this study, the observed records from K-NET near tank sites where sloshing occurred were collected, and then adopted to evaluate sloshing height based on the velocity response spectral method. As for data collection of the observed data, Iwaki (FKS011) was chosen for Area-B, Kawasaki (KNG001) for Area-C, and Sakata (YMT001), Shibata (NIG009) and Niigta (NIG010) for Area-D. These observatories are not located in the same place as the oil-tank sites.

Table 2.1 Tank damage in Area-A and Area-B

Area	Causes	Damage features	Typical damage example
Pacific ocean side in Tohoku	Tsunami	Signficant damage due to Tsunami	Movement of tank and pile, fall-over of tank
			Flow-out and scour of foundation of tank and oil-prevention embankement
			Fire at tank
			Failure, deformation and movement of pipe nozzle
			Failure of berth
	Long-period	Damage degree is low	Low sloshing height
			coming off from rail of rolling ladder
			Oil observed in deck of floating roof, but no structure damage of roof
	Short-period	Almost no damage	Damage observed only in one water-storage tank (buckling of shell plate)
Pacific ocean sidein Fukushima and Ibaraki	Tsunami	Damage observed near coastal revetment	Berth damage
	Long-period	Damage degree is low	Low sloshing height
			Oil observed in deck of floating roof (double deck strucutre)
	Short-period	Signficant damage especially liquefaction	Settlement of tank due to liquefaction, damage and collapse of oil-prevention embankment
			Deformation of side plate and opening of top angle part due to tank settlement
			Sand boiling at ground surrouding tank

Table 2.2 Tank damage in Area-C and A-D due to long-period seismic wave

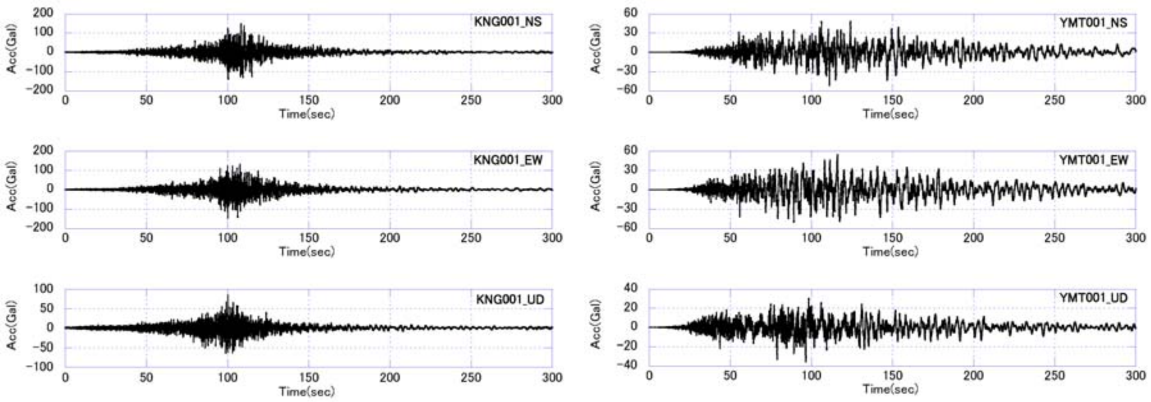
Causes	Damage features	Roof	Typical damage example
Long-period	Damage only due to long-period	Floating roof	Settlement
			Damage of pontoon
			Overflow from top of side plate
		Cover roof with iner float	Damage of steel pontoon, oil inside pontoon
			Oil in simple floating aluminum cover
Long-period	Damage only due to long-period	Floating roof	Oil in pontoon(including one tank that meets requriments of new standard on floating roof)
			Damage and deformation of attachements
			Deformation of deck of pontoon
			Overflow from top of shell
		Internal floating cover	Failure of inner floating
			Deformation of floating tube

Table 2.3 indicates the maximum horizontal and vertical accelerations at selected K-NET stations and their epicentral distances. Acceleration waveforms at KNG001 (Area-C) which is located about 400km from the epicenter, and those at YMT001 (Area-D) which is located about 280km from the epicenter are shown in Fig. 2.2(a) and Fig. 2.2(b), respectively. The maximum acceleration at KNG001 has larger than that at YMT001 site. However, the acceleration wave at YMT001 site has longer duration.

Figure 2.3 shows the Fourier spectra of acceleration waves at the two sites. Peak amplitude could be observed at around 0.7-0.9 seconds at KNG001 site, and around 3-7seconds at YMT001 site. These differences are considered to be due to the source and path effects, and the details will be clarified in future studies.

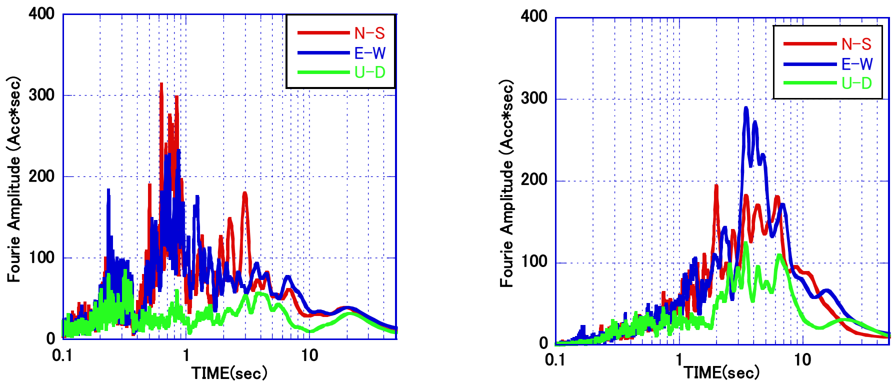
Table 2.3 PGA and epicentral distance

Area No.	K-NET	SITE	Max. Acc(Gal)		Δ (km)
			Hor.	UD	
B	FKS011	Iwaki	373.5	300.1	206
C	KNG001	Kawasaki	148.9	87.3	401
D	YMT001	Sakata	54.9	35.6	280
D	NIG009	Sibata	29.5	13.3	309
D	NIG010	Niigata	35.0	13.8	338



(a) KNG001 (b) YMT001

Figure 2.2 Observed Acceleration waveform



(a) KNG001 (b) YMT001

Figure 2.3 Comparison of an acceleration Fourier spectrum at two sites

2.3. Evaluation of sloshing height

Since there is limitation in the use of recorded seismic data at the tank sites, the observed data at K-NET stations Area-B, Area-C and Area-D were employed. As for the diameter of tank, oil depth and observed sloshing height, the information from NRIFD (2011) are used. Using these data, the evaluation of sloshing height is performed as shown in Table 2.4.

Table 2.4 shows diameter (Dir.(m)), oil level (Height(m)), fundamental period of sloshing (sec.), observed sloshing height (H.O.(cm)), and computed sloshing height(H.C.(cm)) also the sloshing height evaluations.

Table 2.4 Comparison the measured and calculated sloshing height

Area No.	K-NET	SITE	Tank		Sloshing		
			Dir. (m)	Hight (m)	Perid (sec)	H. O. (cm)	H. C. (cm)
B	FKS011	Iwaki	62.5	10.2	11.3	60	87
			74.6	21.5	10.2	29	121
C	KNG001	Kawasaki	38.7	19.7	6.7	-	138
			52.0	16.4	8.3	-	123
D	YMT001	Sakata	25.4	6.7	4.2	-	232
	NIG009	Sibata	48.4	13.3	8.2	180	61
			78.5	19.0	11.0	188	96
	NIG010	Niigata	25.2	8.3	5.7	136	142
			76.0	19.1	10.7	178	214

Relatively good agreement could be confirmed between the observed and the computed sloshing heights using recorded waves at K-NET in Niigata region. In other regions, however, the degree of agreement between the observed and the computed sloshing heights is not satisfactory. Especially in Shibata region, the observed sloshing height is about 2m (Zama 2012) while the computed one using recorded waves at K-NET is about only half of the observed result.

Thus, it is necessary to carefully study the difference of seismic ground motion characteristics near the tank sites and K-NET observation site to evaluate sloshing height using recorded seismic data at K-NET.

3. OUTLINE OF SYSTEM

In the real-time prediction of sloshing using EEW, the sloshing height of oil storage tank is predicted before the arrival of the seismic wave at a tank site, and the ranking of the degree of damage due to sloshing is computed for reducing of the possible damage (Ohbo,2005 , Zama,2009). In addition, the damage of floating roof of tank (Ohbo,2010) and the bucking of shell plates due to strong ground motions are evaluated. These functions were integrated as a system (Ohbo, 2011).

The systems are evaluated oil-overflow, floating roof damage and buckling damage before the arrival of seismic wave at a tank site using EEW, and could efficiently monitor the situation of many tanks. Figure 3.1 indicates the flowchart of damage evaluation.

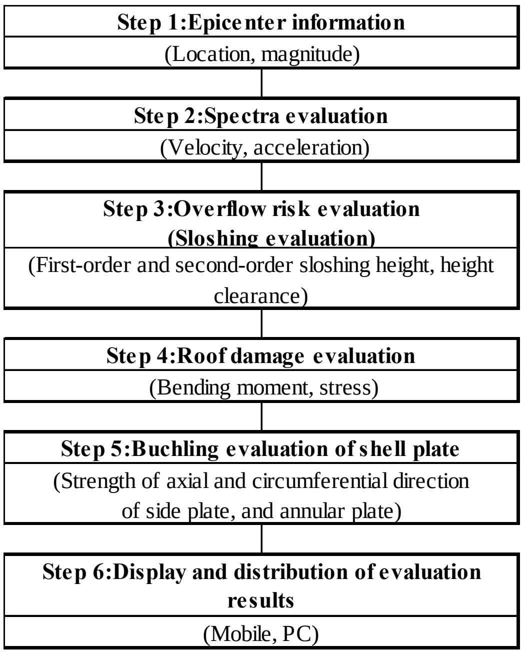


Figure 3.1 Tank damage evaluation flow

3.1. Prediction Spectrum

Response spectrum is predicted using the epicenter location, depth and magnitude of earthquake from EEW. There have been few researches on distance attenuation of long-period seismic waves that induce sloshing of liquid in a tank. In this system, the method proposed by Zama (2000) is adopted. In this method, the attenuation curves for the response spectrum is computed for each seismic zone using recorded data, because long-period seismic wave is considered to mainly consist of surface wave, and source characteristics and effects of propagation path are needed to be taken into account. The details of the method are described in the reference (Zama 2000).

As an example, the distance attenuation formula for velocity spectrum Fc(T) in the case of subduction zone is shown as follows.

$Fc(T) = 4.8 \cdot 10^{0.5M-1.5} \exp(-\alpha \cdot r) / r^{0.5}$ (6.9 ≦ M).
$Fc(T) = 4.8 \cdot 10^{1.25M-6.7} \exp(-\alpha \cdot r) / r^{0.5}$ (6.2 ≦ M<6.9).
$Fc(T) = 4.8 \cdot 10^{0.5M-2.1} \exp(-\alpha \cdot r) / r^{0.5}$ (M<6.2)

The characteristics of long-period ground motions vary with the location of epicenter (ZONE) and region. The region-based variation could be identified by comparing observed data with standard spectrum which reflects the average characteristics of source and propagation path. A ZONE is considered as a region where earthquake mechanism is similar (seismo tectonic zone), and appropriate scaling law for spectrum is employed. As the propagation characteristics are almost the same for all particular sites in the same ZONE, the regional characteristics are used to predict spectra of arbitrary earthquakes occurred in the ZONE.

As for the seismic evaluation of tank damege, acceleration spectrum evaluation is necessary in order to predict short-period ground motion. Through the analysis of observed seismic data at Mutsu-Ogawara storage base, a good agreement has been confirmed over the range from short-period to long-period (Hikita,2010).

3.2. Tank damage evaluation due to long-period ground motion

3.2.1 Evaluation of sloshing height and overflow eisk
Based on the velocity potential theory, sloshing height using the velocity response spectrum and overflow risk of liquid are evaluated at a period of the sloshing period determined using the diameter and oil level of a tank.

3.2.2 Evaluation of floating roof damage
According to Japan Fire Service, floating roof of a single deck plate structure must be designed such that liquid motion would not cause structural damage, for the oil storage tank in the following conditions,
1) Capacity is equal or larger than 20,000KL
2) Distance between roof and top of shell plate is larger than 2m, even capacity is less than 20,000KL,

In addition to the first sloshing mode, the second sloshing mode significantly affects the aseismic strength of floating roof. Therefore, the transversal stress in pontoons must be less than allowable stress under the following loadings induced by liquid sloshing.
1) Out-of-plane bending moment in circumferential direction
2) In-plane bending moment on horizontal plane
3) Compressive force in circumferential direction
The details of stress and loading evaluation are represented in references (FDMA,2005).

3.3. Buckling evaluation due to short-period ground motion (FDMA,1974, Zama,2002)

Based on the Japan Fire Serves Law, the following stresses to the shell plate of tank due to strong ground motion are indicated as follows.
1) Tensile stress of shell plate in circumferential direction during earthquakes
2) Compressive stress of shell plate in axial direction during earthquakes
3) Horizontal loading capacity of annular plate during earthquakes

While horizontal and vertical design spectra are used for defining loading conditions in the evaluation of tank strengthe acceleration response at natural period depending on diameter of tank, side plate thickness, liquid depth is employed, when using seismic records, to evaluate capacity of shell plate and horizontal bearing capacity of annular plate, and to calculate the strength of tank.

The tensile stress in shell plate in circumferential direction is computed using static liquid pressure, and dynamic pressure corresponding to horizontal/vertical design spectra and allowable stress. If the computed stress is larger than 50% of yield stress of tank material, it is considered dangerous.

The compressive stress of shell plate in axial direction is calculated using vertical loading, moment of shell plate, section area, and section coefficient of shell plate. It is judged as dangerous status if the stress exceeds 50% of yield stress of material.

Horizontal allowable strength of annular plate is evaluated considering uplifting resistance force, structural characteristics coefficient and effective mass of liquid. It is considered dangerous if seismic horizontal loading capacity exceeds 50% of horizontal design capacity of tank.

3.4. Outline of instruments and application of evaluation results

3.4.1 Outline of instruments

Figure 3.2 shows the instrument with evaluation system of tank safety using EEW. The instrument obtains EEW through internet, and automatically displays the evaluated result on PC that is connected to internet and distributes the result to outside Email addresses at the same time.

The specification of the instrument is as follows.

・81(W)×133(D)×32mm(H),

・CPU：600MHz,

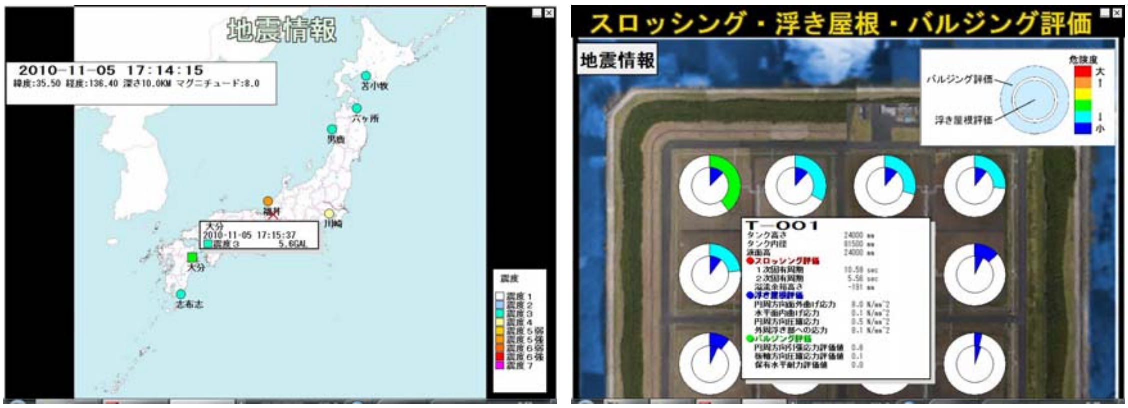
・Main memory： 1 GB

Figure 3.2 General View of the System

3.4.2 Display of evaluation result

The system obtains EEW, and automatically displays the predicted seismic intensity and arrival time for the objected area on PC. Figure 3.3(a) indicates an example.

Figure 3.3(b) shows an example displaying risk of overflow of oil, failure of floating roof and buckling tank structure risk of tank. The area of outside of circle shows buckling tank structure risk and inside of the circle indicates damage risk of floating roof. If a specific tank is clicked, the following information will be displayed: tank name, tank information, first and second natural sloshing periods, distance from the max sloshing height to topangle, stresses onto floating roof, and stress onto tank structure.



(a) Seismic intensity of an object sites (b) Example of Tank Damage

Figure 3.3 Example of an evaluation result display screen

In addition, the risk ranking is distributed to PC and mobile phones through the internet and at the same time the predicted results of damage regarding sloshing, floating roof and shell plate will be displayed.

4. EVALUATION OF SLOSHING USING EEW

In this study, in order to confirm the validity of the developed system, the sloshing height is computed using EEW and earthquake information issued by JMA during the 2011 off the Pacific coast of Tohoku Earthquake.

Figure 4.1 indicates the distribution of tank sites for the evaluation. The background information is the distribution of SI value issued by National Research Institute for Earth Science and Disaster Prevention (2011).

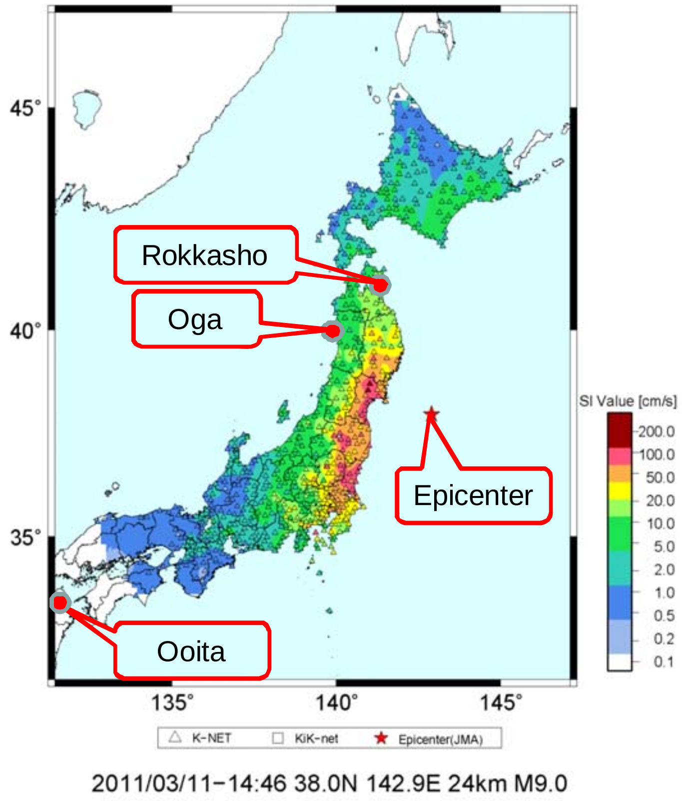


Figure 4.1 The point for calculation of sloshing height and Epicentre (corrected NIED 2011)

In this earthquake, seismic wave was detected at 14:46:40.2, and the first EEW was distributed 5 seconds later at 14:46:45.6. The magnitude was issued as 4.3. The final EEW was 117 seconds after the detection of P wave at 14:48:37.0. The distributed information was as follows. Magnitude: 8.1; Focal depth: 10km, Location: north latitude 38.1deg, east longitude 142.9deg. JMA modified the earthquake information afterwards as follows. Magnitude: 9.0; Focal depth: 24km; Location: north latitude 38.6.2deg, east longitude 142.51.6deg (JMA 2011). This information is employed to compute sloshing height for tank located at Rokkashou, Oga and Oita. Table 4.1 shows the calculated sloshing height using EEW information and earthquake information from JMA. The tank information, observed sloshing height, horizontal and vertical maximum acceleration and epicentral distance (Δ) are also shown in the table.

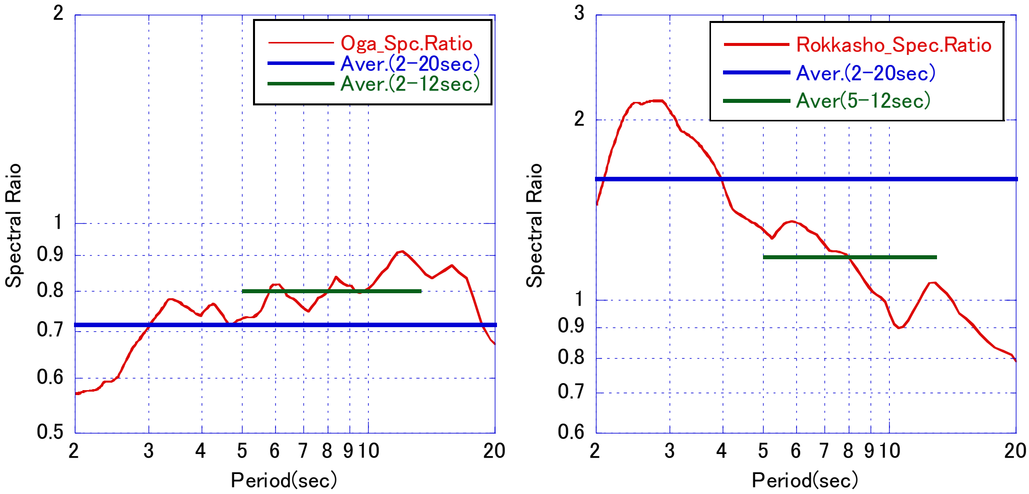
Table 4.1 Sloshing height calculated using EEW and earthquake information

Site	Tank	Tank Size		Sloshing Height(cm)			PGA(Gal)		Δ(km)
	Cat.	D(m)	H(m)	Obs.	M=8.1	M=9.0	Hor.	UD	
Rokkasho	Ground	81.5	20.8	50	34	117	130.6	56.8	342
Oga	Ground	82.4	20.6	63	35	122	22.7	14.5	324
	In-Ground	90.0	48.0	76	45	156			
OOita	Ground	83.3	22.0	11	7	22	2.7	1.4	1145

The computed result is about 60% of observed one when using EEW, and about two times as large as observed one when using earthquake information that M=9.0. Even at tank site in the Oita which is located 1145km from the epicenter, the observed sloshing height reaches to 11cm. The computed sloshing height at this site is 22cm when using earthquake information. The similar tendency is observed at other two tank sites as well.

The standard spectrum evaluations, the data at each meteorological station were used. Therefore, it is necessary to modify the spectrum when objective site is far from the meteorological station. In order to compare the response characteristics at each tank site with the standard spectrum at Hachinohe and Akita meteorological stations, the observed seismic waves at these tank sites are used to calculate the spectral ratio between observed and standard responses at meteorological stations.

Figure 4.2 shows the acceleration response spectral ratio at periods from 2 to 20 second and the average of observed waves recorded during the 2011 off the Pacific coast of Tohoku Earthquake at Oga and Rokkasho tank sites and standard ones at Akita and Hachinohe meteorological stations, the average value over sloshing periods from 5 to 12 seconds is also indicated.



(a) Oga Site (b) Rokasho Site

Figure 4.2 The acceleration response spectral ratio to the Akita and the Hachinohe meteorological observatories

It can be seen from the figure that the observed average at tank site is about 80% of the standard one at the meteorological station for the Oga site, and 117% for the Rokkasho site. The spectral ratio varies significantly with the site. Using these information, the sloshing height is computed assuming M=9.0, and the result is 98cm and 125cm at Akita, and about 105cm at Rokkashou using spectrum ratio over sloshing period range. On the other hand, when M=8.1 is used which was distributed through EEW, a good agreement could be confirmed between calculated and observed results.

A good agreement is achieved between observed and predicted result using the system when EEW is adopted. However, the predicted result by the system is larger than the observed one when using the earthquake information issued after the earthquake.

In the future implement of the system, it is possible to evaluate the standard spectrum of objective site using K-NET data and the observed data at the tank site in the past.

5. CONCLUSIONS

The results of the study can be summarized as follows.

1) Through the collection and analysis of K-NET data near the site of damaged tanks in the 2011 off the Pacific coast of Tohoku Earthquake, it is confirmed that the seismic characteristics in the region on Pacific Ocean side are different from those on Japan Sea side. In addition, the observed sloshing height is compared with predicted result using K-NET data, and it is clarified that the sloshing height could be calculated using K-NET data. It is also shown that the developed system could be used for earthquake disaster prevention and mitigation of tank yard due to long-period seismic wave if K-NET data, which is operated by National Research Institute for Earth Science and Disaster Prevention, could be obtained in real-time.

2) The observed sloshing heights during the 2011 off the Pacific coast of Tohoku Earthquake are compared with the computed results by the system developed by the authors using the distributed EEW. The system can evaluate damage of oil overflow and damage of floating roof due to long-period seismic wave, and buckling of shell plate damage due to short-period ground motion using EEW during large earthquakes. However, availability for short period ground motions could not verified because there were little observation data for tank damage.

3) The evaluated sloshing values using magnitude by JMA are larger than the observed ones. It is confirmed that the degree of agreement could be improved by modifying the spectrum at the objective site.
4) The aspects for further investigation and improvement are clarified. The preparation of spectral modification function for each seismic area could improve the accuracy if the accurate magnitude during large earthquakes could be distributed through EEW.
The authors will continue the investigation on the practical applicability of the system.

AKCNOWLEDGEMENT
The author gratefully acknowledges support from Mrs. Sachiko Inagaki of Eisinsystem Co. Ltd for her efforts on analysing earthquake records. Moreover, K-NET (National Research Institute for Disaster Prevention) data were used.

REFERENCES

FDMA(1974). Notification to determine the item of the technical standard about the regulation of dangerous materials, *FDMA*. (in Japanese).
FDMA(2005). About the enforcement such as departmental orders to revise a part of the rule about the regulation of dangerous materials, *FDMA*. (in Japanese).
Hazrdous Materials SafetyTechniques Association (KHK). (2011). The damage outline of a dangerous facility in the 2011 off the Pacific coast of Tohoku Earthquake, *Safety & Tommorow*, **No.138**, pp.16-27. (in Japanese)
Hikita T., Ohbo N., Kato K., Tuchida T., Iwata K., Zama S., and Hori M. (2010). Earthquake motion evaluation of the northern offing earthquake of assumption Sanriku based on seismic observation record, *Japan Society of Civil Engineers 2010 Annual Meeting*, **No.66**, pp.681-682(in Japanese).
Iwahara T., Mitsuta T., Horii Y., Ohbo N., Ishii A., and Hamada T.(2008). Safety Assessment of Underground Tank from Long-Period Strong Ground Motion −Development of Earthquake Disaster Warning System Using Real-Time Earthquake Information-, *14WCEE*.
JMA http. What is an Earthquake Early Warning?. *http://www.seisvol.kishou.go.jp/eq/EEW/kaisetsu/Whats_EEW.htm*. (In Japanese).
JMA (2011). About the announcement situation of the EEW, *http://www.seisvol.kishou.go.jp/eq/EEW/kaisetsu/teikyoujoukyou_201103.pdf*, (in Japanese).
NIED(2011). Observed K-NET data of the 2011 off the Pacific coast of Tohoku Earthquake. *NIED*
NRIFD (2011). The investigation report about the damage and fire-fighting activity in the 2011 off the Pacific coast of Tohoku Earthquake (1st Report), *Techinical Report of NRIFD*, **No.82,** pp.253-374. (in Japanese)
Ohbo, N., and Kato, K., (2005). Development of Real-Time Sloshing Evaluation System, *Proceedings of the Mini-Symposium on technology for mitigation of sloshing damages for large tank*, pp.15-18. (in Japanese).
Ohbo, N., and Zama S., Sato M., and Takada F. (2010): Development of Safety Evaluation System of Oil Strage Tanks Based on Seisimic Information, *ISSS*, **No.26,** pp.15-18. (in Japanese with English abstract).
Ohbo, N., Meguro K., Zama S., Sato M., and Takada F. (2011). Development of various damage prediction systems of the tank using urgent EEW, *Japan Society of Civil Engineers 2010 Annual Meeting*, **No.66,** pp.15-18. (in Japanese).
Zama S. (2000).Semi-EmpricalExpression for Accelelation Spectrum of Long-Period Strong Ground Motion, *Report of National Reseearch Insituite of Fire and Disaster*, **No.89**.
Zama S. (2002). Building a Real Time System for Evaluating Oil Strage TankDamage due to Eartqkaues Petroleum Stocking Bases, *JHPI*, **Vol40. No.3**. (inJapanese with English abstract)
Zama S., (2004). Effective Collection of Eartquake Damage Information and Its Utilization to Fire Fighting just after an Earthquake, *13WCEE*, **Paper No.3202**.
Zama S., and Endo M. (2009). Real Time prediction of Liquid Sloshing of Oil Strage Tank Based on Earthquake Earrly Warning, *Report of NRIFD*, **No.106.** pp17-22. (inJapanese with English abstract).
Zama S., et al. (2012). On damage of oil strage tanks due to the 2011 off the Pacific coast of Tohoku Earthquake (Mw=9.0), Japan, 15WCEE submitted.