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ANALYSIS OF LONG-PERIOD GROUND MOTIONS OBSERVED BY TANK DAMAGE EVALUATION SYSTEM AND PREDICTION OF SLOSHING HEIGHT

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Abstract

As the sloshing of oil caused fire at tank site in Tomakomai area in the 2003 Tokachi-oki Earthquake, the tank damage evaluation system was developed which could observe ground velocity at the tank site, calculate pseudo velocity response spectrum of sloshing period of the tank in real-time and evaluate the sloshing height of all the tanks at the site. In addition to the evaluation of sloshing, the system could evaluate the stress state of tank shell due to short-period ground motions and report seismograms, evaluated sloshing height and stress by email. The development of the system started in 2007, and the system had been gradually installed in 5 special disaster prevention areas in Petroleum Industrial Complexes and Other Petroleum Facilities in Japan. After the completion of the installation in the end of 2010, the Great East Japan Earthquake occurred in March of 2011, during which all the systems installed in the special disaster prevention areas operated correctly, and the calculated sloshing heights by the system were in very good agreement with the observed ones. The validity of the systems was verified.

In this paper, the characteristics of long-period ground motions are evaluated and the effects of long-period ground motions on the sloshing of tank are clarified, using the observed ground motions by the system during period from 2011 to July 2019. The observed ground motions during which the sloshing height was above 10cm, are selected for analysis. The chosen 10 earthquakes are the earthquake occurred on March 11, 2011, Kumamoto Earthquake in 2016, Yamagata Earthquake in 2019, and etc. In the analysis of long-period ground motions, the pseudo velocity response spectra are compared over the period from 1 second to 20 seconds, including 12seconds which is the fundamental period of sloshing of large-scale tank. Source spectrum contained long-period components, which could be observed at a site which is far away from the epicenter because the long-period motion attenuation is not remarkable.

The selected observed ground motions are analyzed and the future sloshing occurring possibility studied. The main conclusions are as follows. 1) In the Great East Japan Earthquake with magnitude of 9, source spectrum included long-period components, and as the energy of the earthquake was very large, sloshing height of around 10cm was observed in special disaster prevention OIT area in Kyushu where is located about 1100km from the epicenter. It was found that the peak ground velocity in MTO area was larger than that in AKT area, while the sloshing height in AKT area was higher than that in MTO area due to the effects of ground structure in AKT area on the propagation of long-period ground motions.2) In Kumamoto Earthquake with magnitude of 7.3, ground motions were observed in OIT and SBS special disaster prevention area. The sloshing heights of OIT and SBS were 1.04m and 0.1m. This is caused by the fact that propagation characteristics of long period motions in two sites from the epicenter are different. 3) From the analysis results, it was found that the long-period ground motions were caused by the source spectrum and propagation characteristics from source to the objective area. 4) Large sloshing height is predicted at AKT site in Special Disaster Prevention Area during the earthquake assumed to occur in Japan Sea. This is the result under the assumption that the characteristics of long-period ground motions at AKT site are the same as at JMA site. In the further research, the observed seismic motions in Special Disaster Prevention Area are to be analyzed and the deep subsurface structure around the tank site ground will be investigated.

Keywords: Long Period Ground Motion, Large Scale Tank, Sloshing, Tank Safety Assessment System

1. Introduction

As the sloshing of oil caused fire at tank site in Tomakomai area in the 2003 Tokachi-oki Earthquake, the tank damage evaluation system was developed which could observe ground velocity at the tank site, calculate pseudo velocity response spectrum of sloshing period of the tank in real-time and evaluate the sloshing height of all the tanks at the site. In addition to the evaluation of sloshing, the system could evaluate the stress state of tank shell due to short-period ground motions and report seismograms, evaluated sloshing height and stress by email. The development of the system started in 2007, and the system had been gradually installed in 5 Special Disaster Prevention Areas in Petroleum Industrial Complexes and Other Petroleum Facilities, such as Mutsuogawara (MTO), Akita (AKT), Fukui (FKI), Ooita (OIT) and Shibushi (SBS), in Japan.

After the completion of the installation in the end of 2010, the Great East Japan Earthquake occurred in March of 2011, during which all the systems installed in the Special Disaster Prevention Areas operated normally, and the calculated sloshing heights by the system were in very good agreement with the observed ones. The validity of the systems was verified [1, 2].

In this paper, the characteristics of long-period ground motions are evaluated and the effects of long-period ground motions on the sloshing of tank are clarified, using the observed ground motions by the system during period from 2011 to July 2019. The observed ground motions during which the sloshing height was above 10cm, are selected for analysis.

2. Tank damage evaluation system

In the real-time prediction of sloshing using observed ground motion at a tank site, the sloshing height of oil storage tank is evaluated, and the ranking of the degree of damage due to sloshing is computed for the reduction of the possible damage [3, 4]. In addition, the damage of floating roof of tank and the bucking of shell plates due to strong ground motions are evaluated [5]. These functions were integrated as a system [6].

The systems (Model KAES-S [7]) could evaluate oil-overflow and buckling damage at a tank site using observed ground motion during earthquakes and could efficiently monitor the situation of many tanks. Figure 1 indicates the flowchart of damage evaluation. Table 1 shows specifications of the installed seismographs (Model VSE-355EI [8]), which could record ground velocity of period until 20 seconds with high accuracy.

In this system, the ground motions recorded by seismographs are processed in real time, and the sloshing height is computed instantly, and the results are distributed to the managers in charge of disaster prevention. The fundamental functions of the system are as the followings.

(1) When seismograph starts to record the ground motion, the trigger information is sent out and the start of the system is reported.

(2) Within the same network, the earthquake information is automatically displayed on the screen of PC. The mark is displayed, and the color of the mark is corresponding to the degree of risk.

(3) Earthquake information is distributed to PCs and cell phones.

(4) The comparison between results of sloshing height and tank height is distributed.

The system starts the distribution of trigger status information when seismographs start recording, and then the peak acceleration/velocity and instrumental seismic intensity after the arrival of the maximum amplitude of ground motions are sent to the cell phones and PCs of the managers in charge of disaster prevention. The ground motion information is to be used in disaster prevention.

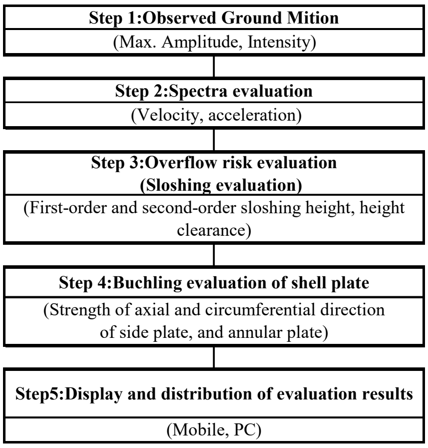

Fig.1 - Tank damage evaluation flow

Table 1 - Specifications of servo velocity seismometer

Model of operation	Horizontal*2, Vertical*1
Bandwidth	0.018～100Hz (-3db)
	0.05～70Hz (±3%)
Ful scale range	Velocity ±200Kine
	Acceleration ±2000Gal
Sensitivity	Velocity 2V/kine
	Velocity 50mV/kine
	Acceleration 5mV/gal
Resolution	Velocity Less than300μkine
	Acceleration Less than300μgal

2.1 Tank damage evaluation system

2.1.1 Evaluation of sloshing height and overflow risk

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

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 [9].

2.1.2 Buckling evaluation due to short-period ground motion [10, 11].

Based on the Japan Fire Serves Law, the following stresses of the shell plate of tank due to strong ground motions 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) Ultimate lateral strength of annular plate during earthquakes

While horizontal and vertical design spectra are used for defining loading conditions in the evaluation of tank strength, the recorded acceleration responses at natural period which depends on diameter of tank, shell plate thickness and liquid depth, are employed to evaluate stress of shell plate and ultimate lateral strength 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.

Ultimate lateral 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.

2.2 Areas with system installed

The development of the system started in 2007, and the system had been gradually installed in 5 Special Disaster Prevention Areas (such as MTO, AKT, FKI, OIT, and SBS, see fig.2) in Japan. After the completion of the installation in the end of 2010, the Great East Japan Earthquake occurred in March of 2011, during which all the systems installed in the Special Disaster Prevention Areas operated normally, and the calculated sloshing heights by the system were in very good agreement with the observed ones. The validity of the systems was verified.

3. Observed long-period ground motions

Ten earthquakes during which the computed sloshing height is higher than 0.1m were selected for investigation. These earthquakes were recorded in 5 Special Disaster Prevention Areas (Tank yard: MTO, AKT, FKI, OIT, SBS) during the period from March 2011 to July 2019. Table 2 shows the event number, earthquake occurrence date (date), earthquake magnitude (JMA), epicentral distance (E_Dis (km)), maximum velocity (M_V (kine)) and the computed sloshing height (Hgt (m)) of the selected earthquakes.

Table 2 - List of selected earthquakes

Event	Date			JMA	Depth	MTO			AKT			FKI			OIT			SBS		
No	Year	Mon	Day	M	(km)	E_Dis	M_V	Hgt	E_Dis	M_V	Hgt	E_Dis	M_V	Hgt	E_Dis	M_V	Hgt	E_Dis	M_V	Hgt
1	2011	3	9	7.3	8	338	3.77	0.10	339	2.11	0.17	680	0.16	0.01						
2	2011	3	11	9.0	24	344	15.56	0.50	323	9.37	0.76	637	2.56	0.14	1,144	2.82	0.11	1,315	1.35	0.03
3	2011	4	7	7.2	66	311	4.70	0.14	254	2.65	0.10	563	0.16		1,074	0.18	0.01			
4	2011	6	23	6.9	36	157	6.74	0.17	231	0.83	0.04	706	0.06							
5	2012	12	7	7.3	49	394	5.81	0.16	401	1.32	0.06	720	0.35		1,222	0.26	0.03			
6	2014	3	14	6.2	78										50	6.02	0.14	269	0.62	0.02
7	2016	1	14	6.7	52	167	5.23	0.12	338	0.35	0.02									
8	2016	4	14	6.5	11										101	2.82	0.10	153	0.79	0.02
9	2016	4	16	7.3	12										104	23.21	1.04	155	2.52	0.10
10	2019	6	18	6.7	14				144	4.31	0.14	403	0.10	0.02						

In the Great East Japan Earthquake (Event No.2 on the Table 2, M=9), seismic motions were observed in 5 Special Disaster Prevention Areas, and the maximum velocity and sloshing height at AKT are 9.37 cm/s and 0.76m, respectively. At SBS which is 1300km from the epicenter, the maximum velocity is 1.35 cm/s. In the Kumamoto Earthquake (Event No.9 on the Table 2, M=7.3), the maximum velocity of 23 cm/s and sloshing height of 1.02m were observed at IT which is 104 km from the epicenter. The six earthquakes in Fig. 2 from event No.1 to No.5 and event No.7 are considered to be aftershocks of the Great East Japan Earthquake.

Fig. 2 shows the location of epicenter of earthquakes and the location of tank yards.

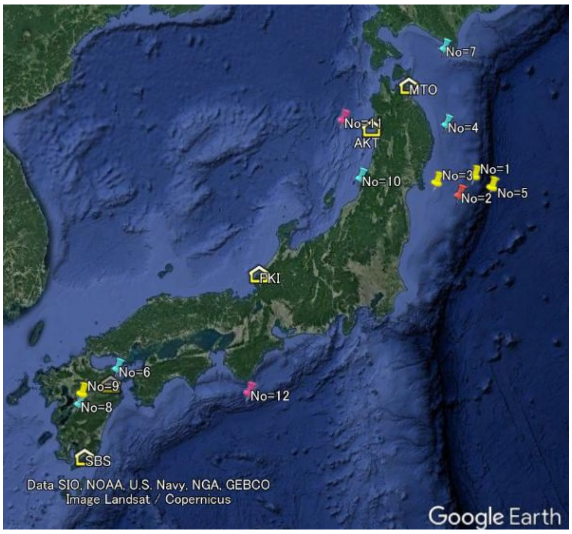

Fig. 2 - Location of epicenter of earthquakes and tank yards

3.1 Relation between earthquake magnitude and sloshing height

Fig.3 shows the relation between earthquake magnitude and observed sloshing height at 5 sites. In the Great East Japan Earthquake with magnitude of 9 (Event No. 2), the maximum sloshing height at AKT is 0.76m. In the Kumamoto earthquake with magnitude of 7.3 (Event No. 9), the maximum sloshing height is 1.04m at OIT. In the earthquakes with magnitude being less than 7, the sloshing height is below 0.2m.

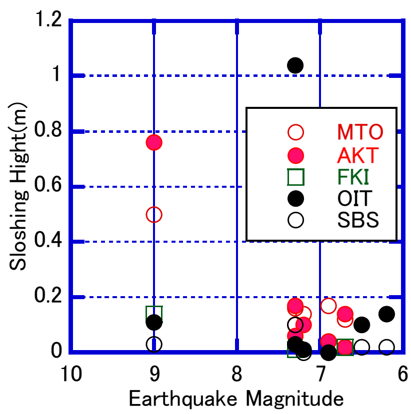

Fig.3 - Relation between earthquake magnitude and Sloshing Height

Sloshing occurs when the seismic motions contain long-period components being equal to the fundamental period of sloshing of tank. The fundamental period of sloshing (Ts) could be calculated by the following formulation.

$$T_s = 2\pi\sqrt{\frac{D}{3.68g}\cdot\coth\left(\frac{3.68H}{D}\right)}$$

Where D: inner diameter of tank; H: oil level (depth of liquid).

Fig. 4 indicates the calculated fundamental period of sloshing of tanks when oil level changes, at 5 tank yards with three typical radius (d=50m, 83m, 90m) [12, 13]. It can be confirmed from the figure that the sloshing would occur when seismic motion contains predominant long-period components from 6 seconds to 15 seconds.

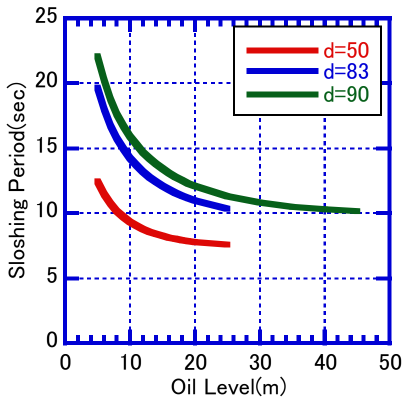

Fig.4 - Relation between oil level and Sloshing Period

3.2 Relation between peak ground velocity and sloshing height

Fig. 5 shows the relation between the peak ground velocity and sloshing height observed at MTO and AKT. The linear approximation results at the two tank yards are also indicated in the same figure. From the gradients of linear equations, it can be seen that the sloshing height at AKT is about 2.3 times as high as at MTO given the same velocity. The results suggest that the ground motions observed at AKT propagated through subsurface structures which excite long-period components of seismic waves.

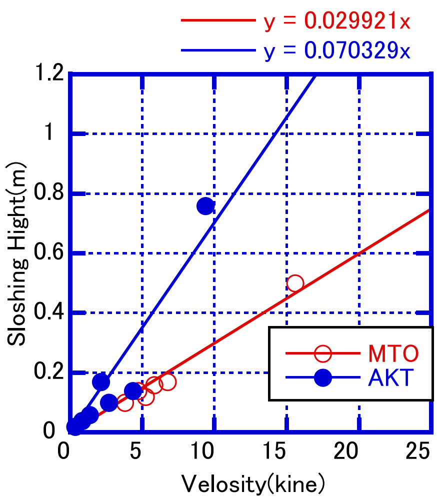

Fig.5 - Relation between Peak Ground Velocity and Sloshing Height

3.3 Long-period ground motions observed at Great East Japan Earthquake

The Great East Japan Earthquake (Mw=9) which occurred on March 11, 2011, caused great damage to civil and building structures with Tsunami and liquefaction. Tank damage was observed in areas which are 300 km～400 km from the epicenter.

In the Great East Japan Earthquake, the typical tank damage on Tohoku Pacific Ocean side and Fukushima-Ibaraki Pacific Ocean side was due to Tsunami. In Tokyo bay, 14 floating roof and floating roof lid damage was observed, and one floating roof sinking was confirmed. On the side of Sea of Japan, destructive damage on aluminum floor and inner lid of mold was observed due to sloshing. In the area, sloshing exceeding the safety level in Fire Service Legislation was confirmed [14, 16].

Fig. 6 shows the Fourier spectra of ground velocity observed at AKT, MTO and OIT. The typical radii of tanks in the area are 83 m and 90 m, and the fundamental periods of sloshing are from 10 seconds to 20 seconds, which are almost the same as the predominant period components in the observed seismic motions, and thus sloshing was confirmed even at SBS site which is far away from the epicenter.

Fig. 7 indicates the relation between epicentral distance and sloshing height. The regression equation was established based on the observed results, although the number of data was limited. According to the regression equation, the sloshing height of a tank with sloshing period of 10 seconds is about 1 m when epicenter distance is 100 km.

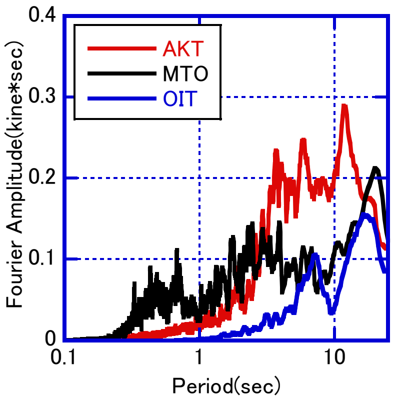

Fig.6 - Comparison of Fourier Spectrum of Velocity at 3 sites

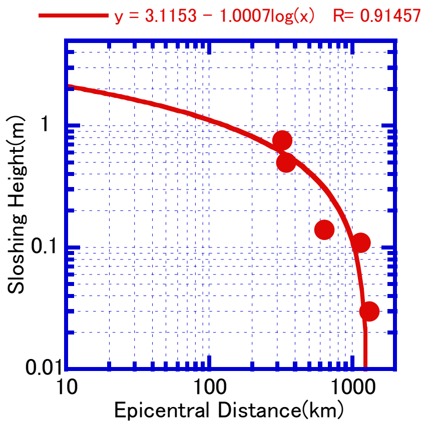

Fig.7 - Relation between Epicentral Distance and Sloshing Height

3.4 Long-period strong ground motions observed in the Kumamoto earthquake

On April 16, 2016, an earthquake with magnitude of 7.3 occurred at 1:25 am. Seismic intensity of 7 (Japan scale) was observed in Mashiki and Nishihara. Strong ground motions were observed in Kumamoto prefecture and other prefectures in Kyushu. It was the first time since 1949 (when intensity of 7 was introduced) that earthquakes with intensity of 7 occurred continuously.

The number of deaths is 44, and number of injured 1814. 8300 houses were completely destroyed, and 160,000 residential houses damaged. Water supply was interrupted for about 450,000 households, electricity supply interrupted for about 480,000 households and gas supply interrupted for about 110,000 households. In the earthquake, oil leaking at OIT was reported [17].

Fig. 8 shows the Fourier spectrum of ground velocity observed at OIT site during earthquake 8 (M=6.5) and 9 (M=7.3). In earthquake 9, predominant components with periods of 6 to 9 seconds could be confirmed which are the same as the sloshing period of tank, and thus it could be considered that sloshing occurred. In earthquake 8, on the other hand, the components with period near the sloshing period of tank is extremely small and the sloshing height is less than 1/10 of that in earthquake 9.

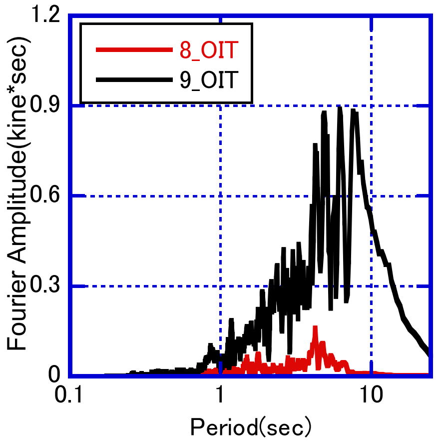

Fig.8 - Event No.8 and No.9 Fourier Spectrum

3.5 Relation between epicentral distance and sloshing

The regression equation was established for the relation between epicentral distance and sloshing height, based on the calculated sloshing height from the observed ground motions at 5 tank yards.

Fig. 9 shows the epicentral distance and sloshing height for earthquakes with magnitude of M6, M7 and M9, respectively. The regression formulations for relation between epicentral distance and sloshing height for each magnitude are indicated in the same figure.

The observed sloshing height of 1 m when M=7 is on the regression curve for M=9. The reason is that in Kumamoto earthquake, the seismic motion contains significant components with the same period as sloshing period of tank at OIT.

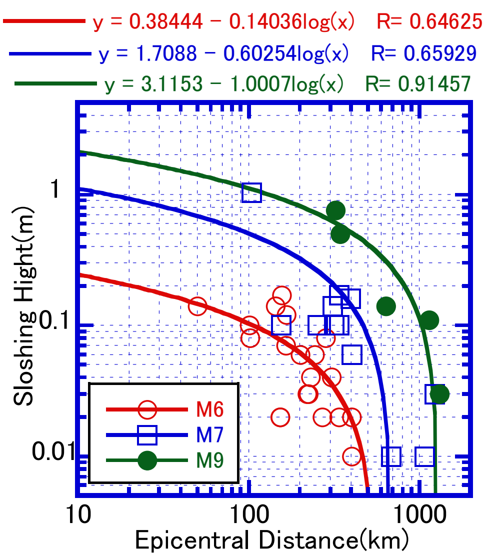

Fig.9 - Relation between epicentral distance and sloshing height for earthquakes with magnitude of M6, M7 and M9

4. Evaluation of sloshing during large earthquakes

By using the real-time sloshing prediction system based on earthquake early warning information [18], the sloshing height was calculated for the No. 25 earthquake (Event No.11 show on the Fig.2, M=8.5) with epicenters in the Japan Sea which has been predicted Akita Prefecture study group on large earthquake investigation committee [19]. Furthermore, the sloshing height was calculated for the earthquake (Event No.12 show on the Fig.2, M=8.6) with epicenter in Nankai Trough [20].

Response spectrum is predicted using the epicenter location, depth and magnitude of earthquake from two earthquakes. There have been few researches on the attenuation relationships for long-period ground motions that induce sloshing of liquid in a tank. In this system, the method proposed by Zama [21] is adopted. In this method, the attenuation curves for the response spectrums computed for each seismic zone using recorded data, because long-period strong ground motion is considered to mainly consist of surface wave, and source characteristics and effects of propagation path (here called regional characteristics) are needed to be taken into account. The details of the method are described in the reference [4, 21].

Using this method, the height of sloshing at JMA site could be calculated. In this study, the height of sloshing was calculated earthquakes with epicenters in the Japan Sea and Nankai Trough with the assumption that the characteristics of long-period seismic motions are same regional characteristics of the target area for evaluation of the Special Disaster Prevention Areas as those nearby JMA site.

Table 3 shows the event number (Event No.), earthquake occurrence site (Site), earthquake magnitude (JMA M), focal depth (Dep (km)), epicentral distance (E.D. (km)), the calculated maximum and minimum sloshing height (S.H.(m), Max, Min) and epicenter distance for sites MTO, AKT, FKI and OIT, two earthquakes with epicenters in the Japan Sea and Nankai Trough, respectively.

In the earthquake with epicenter at Akita-oki, the calculated maximum and minimum sloshing heights at AKT site are 3.28 m and 1.61 m, respectively. The earthquake with epicenters in the Nankai Trough, the maximum sloshing height is 45cm at FKI site where epicenter distance is 328 km, and 68 cm at OIT site where epicenter distance is 393 km.

Table 3 - Sloshing height in Special Disaster Prevention Area during earthquakes with epicenters in the Japan Sea and Nankai Trough

Event No.	Site	JMA M	Dep (km)	MTO			AKT			FKI			OIT		
				E.D.	S.H.(m)		E.D.	S.H.(m)		E.D.	S.H.(m)		E.D.	S.H.(m)	
				(km)	MAX	MIN	(km)	MAX	MIN	(km)	MAX	MIN	(km)	MAX	MIN
11	Japan Sea	8.5	10k	221	1.18	0.50	84	3.25	1.61	503	0.41	0.20	997	0.52	0.23
12	Nankai Trough	8.6	10k	985			820			328	0.45	0.25	997	0.68	0.34

Large sloshing height is predicted at AKT site in Special Disaster Prevention Area during the earthquake assumed to occur in Japan Sea. This is the result under the assumption that the long-period ground motion characteristics at AKT site are the same as at JMA site. In the future research, the observed ground motions in Special Disaster Prevention Area are to be analyzed and the characteristics of long-period ground motions due to the subsurface structure at the site will be investigated. Using the system which could evaluate sloshing height based on Earthquake Early Warming, the sloshing height of tank are calculated by using earthquake information of the great earthquake with epicenters in the Japan Sea and Nankai Trough.

5. Conclusion

The selected observed ground motions are analysed and the future sloshing occurring possibility studied. The main conclusions are as follows.

1) In the Great East Japan Earthquake with magnitude of 9, source spectrum included long-period components, and as the energy of the earthquake was very large, sloshing of around 10cm was observed in special disaster prevention OIT area in Kyushu where is located about 1100km from epicentre. It was found that the peak ground motion in MTO area was larger than that in AKT area, while the sloshing height in AKT area was higher than that in MTO area due to the effects of deep subsurface structure in AKT area on the propagation of long-period motions.
2) In Kumamoto Earthquake with magnitude of 7.3, ground motions were observed in OIT and SBS Special Disaster Prevention Area. The sloshing heights of OIT and SBS were 1.04m and 0.1m. This is caused by the fact that long period motion propagation characteristics in two sites from epicentre are different.
3) From the analytical results, it was found that the long-period ground motions were caused by the source spectrum and propagation characteristics from source to the objective area.
4) Large sloshing height is predicted at AKT site in Special Disaster Prevention Area during the earthquake assumed to occur in Japan Sea. This is the result under the assumption that the long-period seismic characteristics at AKT site are the same as at JMA site. In the further research, the observed seismic motions in Special Disaster Prevention Area are to be analyzed and the deep subsurface structure around the tank site will be investigated.

6. Acknowledgements

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