1305

STUDY OF EARTHQUAKE GROUND MOTION TO EXAMINE SLOSHING IN LNG INGROUND STORAGE TANKS

Osamu WATANABE[1], Atsushi KAMIYA1[2], Takashi OKAMOTO[3] And Shigeru NAGATA[4]

SUMMARY

This paper presents the evaluation of earthquake ground motion severity for the sloshing design of LNG inground storage tanks in the Tokyo Bay area. A pseudo-velocity response spectrum for the sloshing design (for primary sloshing periods of 8 to 10 seconds) is proposed from the analysis of sloshing using earthquake ground motion records and artificial earthquake ground motion generated by a semi-empirical method using small earthquakes recorded in the area. From these analyses, a uniform velocity response spectrum of 180cm/s is proposed for the above period range as the recommended value for the sloshing design of LNG inground storage tanks in the Tokyo Bay area.

INTRODUCTION

Determining how liquids in storage tanks respond to seismic waves with relatively long period components is important for the tank design and safety operation. The Earthquake-Proof Design Code for High-Pressure Gas Manufacturing Facilities [The High Pressure Gas Safety Institute of Japan, 1980] (under the provisions of the High Pressure Gas Safety Law) was used to examine LNG sloshing in inground storage tanks. These standards prescribe that such storage tanks with resonant periods greater than 7.5 seconds shall be examined either by inputting three sinusoidal resonance waves with 60cm displacement caused by the ground motion of earthquake, or by a time history response analysis assuming specific seismic waves for the construction site.

Although there are many previous studies on sloshing phenomena [Inoue, 1986; Noda, 1990; Zama, 1993], researches on sloshing caused by earthquake ground motions is incomplete, and this makes determination of the motion and velocity response spectrum difficult in actual design of tanks against sloshing. The authors studied input earthquake ground motions, in relation to sloshing, to be inputted in the design of LNG inground storage tanks to be constructed in the Tokyo Bay area, Negishi and Ogishima in Yokohama, and Sodegaura in Chiba. The following methods were used: 1) time history response analysis of wave amplitudes by simulating past destructive earthquakes as prescribed in the current High Pressure Gas Safety Law; and 2) obtaining velocity response spectra from simulated earthquake ground motion in the Tokyo Bay area using a semi-empirical method [Takemura and Ikeura, 1988] that includes up to ten-second periods.

EVALUATION OF SLOSHING WAVE HEIGHT UNDER PAST DESTRUCTIVE EARTHQUAKES

Input Seismic Waves

As shown in Table 1, 19 seismograms of 10 earthquake events were used for input values. Earthquakes a) through f) are design earthquake ground motions for the time history response analysis designated in Earthquake-Proof Design Code for High-Pressure Gas Manufacturing Facilities [Ministry of International Trade and Industry, 1982]. Earthquakes a) and b) are based on reference [Building Research Institute, 1965], and [Architectural Institute of Japan, 1976], respectively; c), d), and e) are based on data provided by the Earthquake

---

[1] *Production Engineering Department, Tokyo Gas Co., Ltd., Tokyo Email:w_osamu@tokyo-gas.co.jp*

[2] *Production Engineering Department, Tokyo Gas Co., Ltd., Tokyo Email:a_kamiya@tokyo-gas.co.jp*

[3] *Applied Technology Research Center, NKK Corporation, Kanagawa, Japan Email:tokamoto@lab.keihin.nkk.co.jp*

[4] *Kajima Technical Research Institute, Kajima Corporation, Tokyo, Japan Email:nagata@katri.kajima.co.jp*

Research Institute, University of Tokyo [Tanaka et al., 1979]; and f) is corrected data of the 1978 Miyagi-ken-oki earthquake record [Kurata et al., 1979] using the filter proposed by Goto et al. [Goto et al., 1978]. Seismic record g) came from Nasu and Morioka [Nasu et al., 1973], and records h) through k) came from records of strong-motion seismograph of the Japan Meteorological Agency (JMA). The motion of the 1983 Nihonkai-Cyubu earthquake overshot the capacity of the seismograph; hence, lost parts of the waveforms were added later [Okamoto et al., 1984]. Seismic records l) through q) were based on records of the JMA model 87 strong-motion digital acceleration seismograph [Zama et al., 1994]. Seismic records r) and s) came from the Committee of Earthquake Observation and Research in the Kansai Area. In addition, seismic waves were input at the levels given in the original records.

Analytical method and specifications of storage tanks for analysis

Sloshing-wave responses of the tanks were determined by the axisymmetric linear potential theory with an assumed damping ratio of 0.5 %, and up to the tenth sloshing mode. The tanks for the analysis were six types of inground storage tanks for LNG in the Tokyo Bay area. Table 1 shows the specifications on these tanks and their primary to tertiary sloshing resonant periods. The design depth of liquid in the table is defined as the maximum operational depth of the liquid in a tank in which clearance between the liquid surface and the tank roof becomes the minimum.

Analysis Results

Table 1 shows the maximum sloshing wave height for each seismic wave and storage tank. When NS and EW components were recorded from an earthquake, the maximum sloshing wave height was calculated by synthesizing the two components of the sloshing wave time histories [Zama, S. and Inoue, R., 1994], and is also included in Table 1. Figure 1 shows some results obtained in the time history response analysis of the sloshing wave height at the tank walls. Figure 2 shows some sloshing modes. The response analysis revealed the following:

1) For the 1964 Niigata earthquake (in Kawagishi), the secondary mode dominated such that the maximum amplitude occurred at the tank center instead of the wall (Fig. 2(a)).
2) For the 1923 Great Kanto earthquake, the liquid sloshed in the primary mode in all storage tanks (Fig. 2(b)).
3) For the 1983 Nihonkai-Cyubu earthquake, the initial sloshing varied by tank; it usually increased then decreased, and increased again in some tanks, but almost always in the primary mode for all storage tanks (Figs. 1(a) and 2(c)).
4) For the 1993 Hokkaido Nansei-oki earthquake, liquid sloshed mostly in the primary mode for all tanks (Figs. 1(b) and 2(d)).
5) For the 1995 Hyogo-ken Nanbu earthquake, primary mode sloshing overlapped with higher modes (Figs. 1(c) and 2(e)).

Figure 3 shows the velocity response spectrum values, S_v, obtained by inverse calculations from the primary resonant period, T_c, of the storage tank, and the sloshing wave heights, η_c. The S_v are calculated from the relationship between the velocity response spectra [The Japan Gas Association, 1981] and sloshing wave heights given by

$$\eta_c = 0.00245 \cdot T_c \cdot \tanh(\frac{1.84H}{R}) \cdot S_v(T,h) \tag{1}$$

with

$$T_c = \frac{2\pi}{\sqrt{\frac{g}{h} \cdot 1.84 \cdot \tanh(\frac{1.84H}{R})}} \tag{2}$$

where H is the liquid level (m), R is the tank radius (m), g is the gravitational acceleration, and $S_v(T, h)$ is the velocity response spectrum value (cm/s) for the period $T(s)$ and damping ratio h.

This figure also has the velocity response spectrum values obtained by inverse calculations from the sloshing wave heights given by Eq. (3) [The High Pressure Gas Safety Institute of Japan, 1980]. These calculations were derived from three sinusoidal wave resonance method, a currently used design method prescribed in the High Pressure Gas Safety Law.

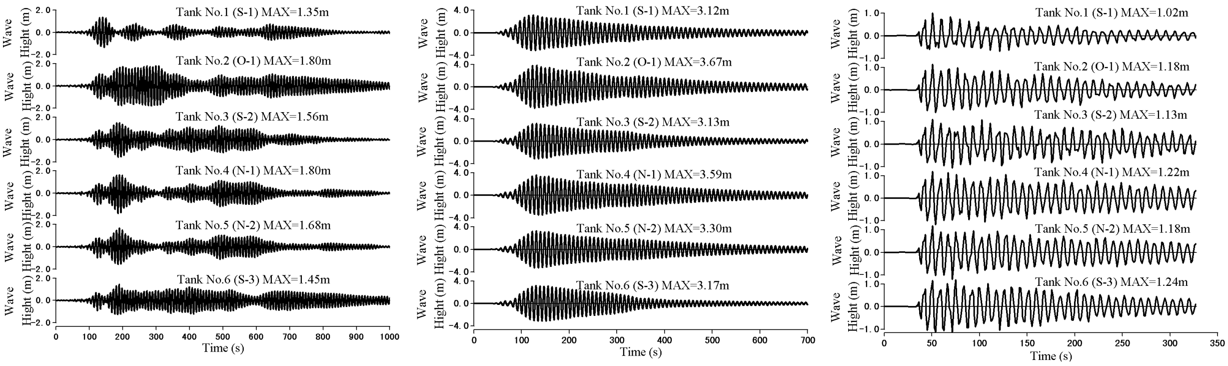
$$\eta_c = \frac{297.4 \cdot D_H \cdot R}{T_c^2 \cdot g} \tag{3}$$

where D_H is the amplitude (cm) of displacement. D_H was 60 cm when the resonant period was above 7.5 seconds and equal to $(50T_c)/(2\pi)$ cm otherwise.

The velocity response spectrum values obtained by inverse calculations from the sloshing wave heights, which themselves came from time history response analysis, was about 180 cm/s (Fig. 3). This is significantly smaller than that obtained by the height calculation formula based on 60cm three sinusoidal wave resonance method as suggested by the High Pressure Gas Safety Law.

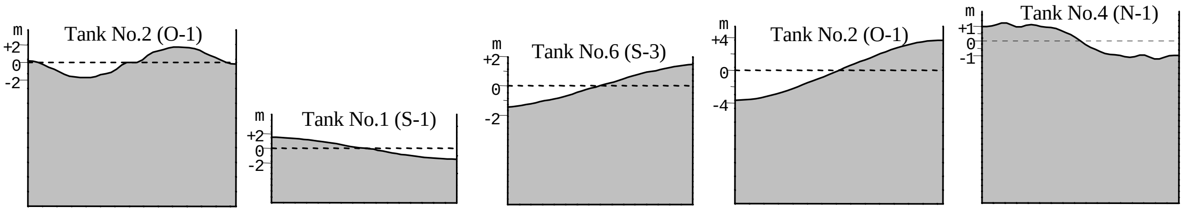
Table 1: Storage tank specifications and sloshing wave height

Tank No.		1	2	3	4	5	6
Location		Sodegaura	Ogishima	Sodegaura	Negishi	Negishi	Sodegaura
Tank label		S-1	O-1	S-2	N-1	N-2	S-3
Capacity (1000 m^3)		60	200	60	200	95	130
Radius :R (m)		32.0	36.0	30.0	34.0	32.0	32.0
Design depth :H (m)		18.7	49.2	21.3	55.1	29.5	40.4
H/R		0.584	1.367	0.710	1.617	0.922	1.263
Resonant period	primary (s)	9.40	8.93	8.72	8.66	8.65	8.45
	secondary (s)	4.93	5.22	4.76	5.07	4.92	4.92
	tertiary (s)	3.89	4.12	3.76	4.01	3.89	3.89
Earthquake		Sloshing wave height : η (m)					
a) 1964 Niigata (Kawagishi) NS		1.76	1.96	1.02	1.54	1.24	1.32
b) 1968 Tokachi-oki (Hachinohe) EW		0.46	0.54	0.47	0.53	0.50	0.51
c) 1933 Sanriku-oki (Tokyo University, Hongo) NS		0.27	0.33	0.38	0.41	0.39	0.29
d) 1974 Izu-hanto-oki (Tokyo University, Hongo) NS		0.30	0.40	0.34	0.39	0.37	0.41
e) 1974 Izu-hanto-oki (Tokyo University, Hongo) EW		0.22	0.26	0.20	0.20	0.21	0.18
f) 1978 Miyagi-ken-oki (Shiogama port) EW		0.34	0.41	0.39	0.42	0.41	0.43
g) 1923 Great Kanto (Tokyo)		1.49	1.30	0.88	0.89	0.83	0.85
h) 1983 Nihonkai-Chubu (Niigata) NS		1.35	1.80	1.56	1.80	1.68	1.45
i) 1983 Nihonkai-Chubu (Niigata) EW		0.65	0.89	1.36	1.78	1.67	1.76
j) 1964 Niigata (Akita) NS		0.24	0.22	0.20	0.31	0.27	0.33
k) 1964 Niigata (Akita) EW		0.52	0.72	0.61	0.67	0.62	0.46
l) 1993 Hokkaido Nansei-oki (Tomakomai) NS		3.12	3.67	3.13	3.59	3.30	3.17
m) 1993 Hokkaido Nansei-oki (Tomakomai) EW		1.34	1.28	1.07	1.27	1.19	1.28
n) 1993 Hokkaido Nansei-oki (Niigata) NS		2.14	1.07	0.84	0.92	0.87	1.10
o) 1993 Hokkaido Nansei-oki (Niigata) EW		0.98	0.68	0.69	0.79	0.75	0.96
p) 1993 Hokkaido Nansei-oki (Akita) NS		0.55	0.77	0.76	0.84	0.79	0.82
q) 1993 Hokkaido Nansei-oki (Akita) EW		0.86	1.36	1.22	1.43	1.31	1.27
r) 1995 Hyogo-ken Nanbu (Amagasaki) NS		0.81	1.08	0.95	1.18	1.18	1.13
s) 1995 Hyogo-ken Nanbu (Amagasaki) EW		1.02	1.18	1.13	1.22	1.18	1.24
Synthesizing N-S and E-W components	1974 Izu-hanto-oki (Tokyo University, Hongo)	0.37	0.47	0.38	0.43	0.42	0.44
	1983 Nihonkai-Chubu (Niigata)	1.36	1.93	1.60	1.86	1.75	1.88
	1964 Niigata (Akita)	0.53	0.72	0.61	0.68	0.63	0.51
	1993 Hokkaido Nansei-oki (Tomakomai)	3.19	3.80	3.22	3.70	3.41	3.29
	1993 Hokkaido Nansei-oki (Niigata)	2.14	1.19	0.99	1.08	1.01	1.28
	1993 Hokkaido Nansei-oki (Akita)	0.95	1.46	1.36	1.60	1.49	1.49
	1995 Hyogo-ken Nanbu (Amagasaki)	1.27	1.58	1.45	1.64	1.58	1.61
60cm three sinusoidal wave resonance method		6.57	8.20	7.17	8.26	7.77	8.15



(a) 1983 Nihonkai-Cyubu (Niigata) NS (b) 1993 Hokkaido Nansei-oki (c) 1995 Hyogo-ken Nanbu
(Tomakomai) NS (Amagasaki) EW

Figure 1: Time history of sloshing wave



(a) 1964 Niigata (Kawagishi) NS (b) 1923 Great Kanto (Tokyo) (c) 1983 Nihonkai-Chubu (Niigata) NS (d) 1993 Hokkaido Nansei-oki (Tomakomai) NS (e) 1995 Hyogo-ken Nanbu (Amagasaki) EW

Figure 2: Sloshing modes

EVALUATION OF EARTHQUAKE GROUND MOTION FOR TOKYO BAY AREA

Analytical Method

Many predictions of earthquake ground motion using the semi-empirical method have been proposed. The authors used the semi-empirical method [Takemura and Ikeura, 1988], taking into account irregular slips of the fault plane, to simulate earthquake ground motion with the primary periods up to 10 seconds for storage tanks in the Tokyo Bay area. This method is applicable to the simulation of earthquake ground motion with periods up to around 10 seconds if earthquake events and their seismograms are carefully selected.

Our procedure for the earthquake strong ground motion evaluation by the semi-empirical method was the following:

1) Select element earthquakes and element seismic waves.

2) Examine the effective period range of the element seismic waves.

3) Remove the effects of the ground surface layers from the element seismic waves.

4) Synthesis of strong ground motions.

Earthquake Assumptions and Regions Analyzed

Upon selecting the sites in Tokyo Bay area for evaluation, three other regions of high earthquake hazard potential were analyzed [Zama, 1991; Zama, 1993]; 1) the offshore region from Niigata to Akita along the eastern shore of the Japan Sea, 2) off the Boso Peninsula, and 3) around the Izu Peninsula. For these regions, we found the following great past earthquakes relevant for analysis: the 1983 Nihonkai-Cyubu earthquake (M = 7.7), the 1605 Tokai earthquake from the fault on the north side (M = 7.9), and the 1978 Izu-Oshima earthquake (M = 7.0). Furthermore, South Kanto and Tokai, which have established disaster prevention measures in anticipation of great earthquakes, need further study because the forces from earthquake components of long periods have not yet been adequately studied. Therefore, we included hypothetical South Kanto and Tokai earthquakes with JMA magnitudes of 7.9 and 8.0, respectively. The 1983 Nihonkai-Cyubu earthquake was omitted because reliable accelerograms with periods up to 10 seconds were already observed at Negishi.

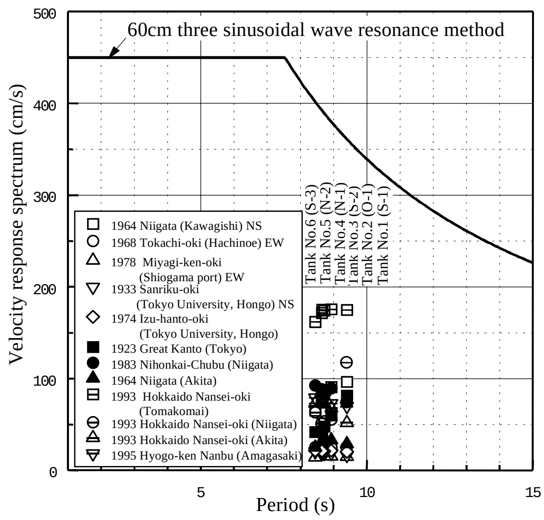


Figure 3: Primary resonant periods and velocity response spectra

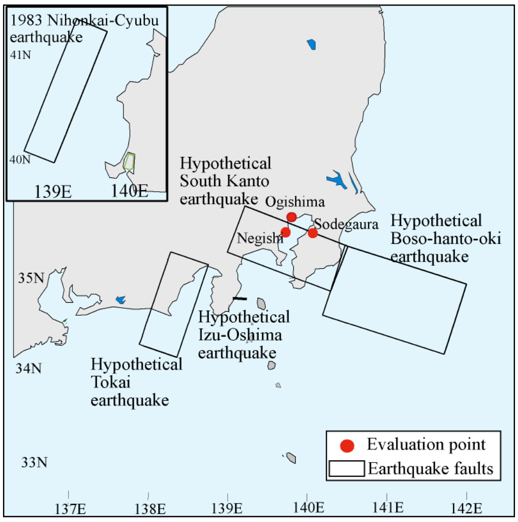


Figure 4: Assumed earthquake faults and evaluation sites

Figure 4 shows the locations of fault planes for these five earthquake scenarios and evaluation points in the Tokyo Bay area, while Table 2 has parameters of the faults. Previous studies [Kanamori, 1971; Ishibashi, 1981; Aida, 1981; Simazaki and Somerville, 1979] were referred to determine these parameters, types, and starting points of ruptures. They were selected so earthquake components with periods of 8 to 10 seconds predominated as much as possible.

Table 2: Fault parameters for earthquake scenarios

Earthquake	Length	Width	Depth to fault top	Strike	Dip	Slip	Seismic moment	Rupture velocity	Rise Time	Rupture mode
	(km)	(km)	(km)	(degree)			(x10^{26} dyne¥cm)	(km/s)	(s)	
Hypo. South Kanto	130	70	5	290	34	162	76.0	3.0	5.0	Unilateral rupture starting from west end
Hypo. Tokai	120	50	2	198	20	60	90.0	2.7	8.6	Radial rupture starting from center of west end
Hypo. Boso-hanto-oki	150	100	1	287	30	154	530.0	3.0	5.0	Unilateral rupture starting from east end
Hypo. Izu-Oshima	17	10	2	270	85	188	1.1	3.0	2.5	Unilateral rupture starting from west end

Selection of Earthquake Events and their Seismograms Used in Semi-empirical Method

In a semi-empirical method, the focal characteristics and similarity of wave propagation of small earthquake events are used to estimate ground motion, earthquake events and their seismic waves were selected according to the following.

1) medium and small earthquakes that occurred inside or around the earthquake faults and, more importantly, had similar propagation path.

2) seismic waves at the evaluation points or from adjacent areas with similar ground conditions.

3) earthquakes with JMA magnitude above 4 as an element earthquake, because the law of similarity for fault parameters is usually applied only when the element earthquake has seismic moments greater than 1022 dynes.

4) as far as practicable, earthquakes with a shallow focus which are more likely to stir up surface waves, which are dominant and exert influence on sloshing.

5) seismic waves with effective periods that are smaller than 10 seconds.

After that, the authors define the earthquake events and their seismic waves by removing the effects of the ground surface layers on the layer upon which the tanks lie from seismic waves observed at the surface and this requires determination of incident waves (2E) on hypothetical open bedrock.

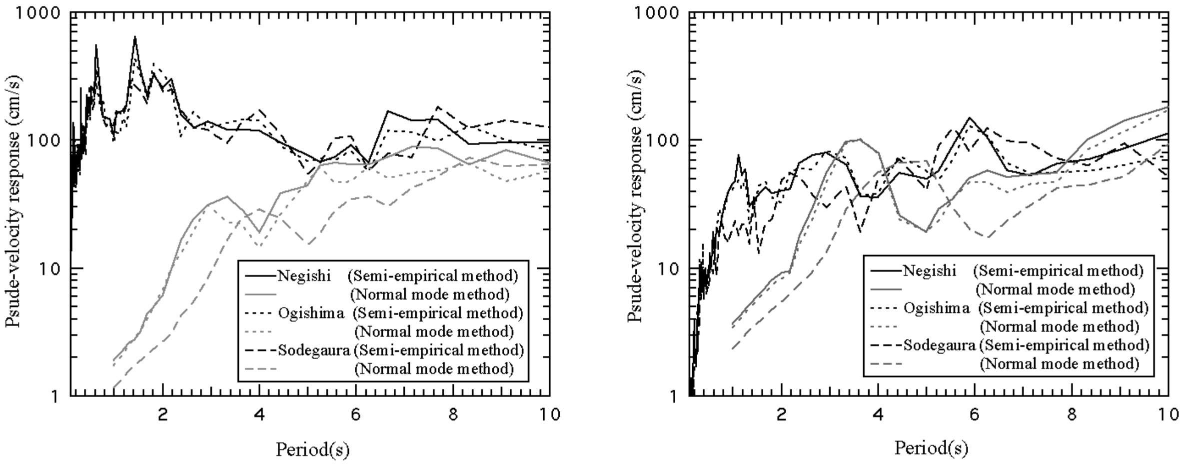
Analysis Results

In the semi-empirical method, the degree of heterogeneity of displacement on fault plane is provided with normal random numbers (mean = 0.0, standard deviation = 1.0), such that the similarity law of earthquake in accordance with the ω^{-2} model. Then we prepared 10 to 30 sample accelerograms for each horizontal components observed at the three study locations, and calculated their pseudo-velocity response spectra (damping ratio: 0.5 %). In addition, the calculation of earthquake ground motion for the points in Negishi, Ogishima and Sodegaura was conducted at bedrock, which is affected limitedly by ground nonlinearities during a great earthquake.

Figure 5 compares six pseudo-velocity response spectrum for Negishi, Ogishima, and Sodegaura in hypothetical South Kanto and hypothetical Tokai earthquakes with more remarkable than those in the other simulated earthquakes. Each curve in the figure is the envelope of the pseudo-velocity response spectra (damping ratio: 0.5 %) calculated from accelerograms with NS and EW components for each site which were obtained by the semi-empirical method.

Previous studies reported that the predominant sloshing periods in the central area differed from those at the recess of the Tokyo Bay area [Niwa et al., 1990; Zama, 1990; Niwa et al., 1993]. We found the dominant peak periods were about 6 or 6.5 seconds at Negishi and Ogishima (in the central area), and around 1, 6, and 8 seconds at Sodegaura (in the recess), in qualitative agreement with the previous reports. However, despite these differences in period of the pseudo-velocity response spectrum, the maximum values of the envelopes for the three sites were all around 150 cm/s at periods of 8 to 10 seconds. These are the primary sloshing periods for 60,000 to 200,000m^3 tanks, a common size for tanks in the Tokyo Bay area.

Additional curves presented for reference in Figure 5 are the results of the pseudo-velocity response spectrum evaluation by the normal mode method [Kudo, 1980], a theoretical method commonly used by previous studies on earthquake ground motion with relatively long periods. We found that this method gave similar results to the semi-empirical method.



(a) Hypothetical South Kanto earthquake **(b) Hypothetical Tokai earthquake**

Figure 5: Pseudo-velocity response spectra (damping ratio is 0.5 %)

Spectra in the Tokyo Bay Area

Figure 6 shows the maximum envelopes of those pseudo-velocity response spectra (damping ratio: 0.5 %) for five earthquake scenarios that were obtained using the semi-empirical method; however, the spectra of the 1983 Nihonkai-Cyubu earthquake was determined using accelerograms observed at Negishi. The hypothetical South Kanto earthquake had its maximum envelope peak between 8 and 10 seconds (which is the primary sloshing period of many LNG inground storage tanks); its maximum value was approximately 150 cm/s.

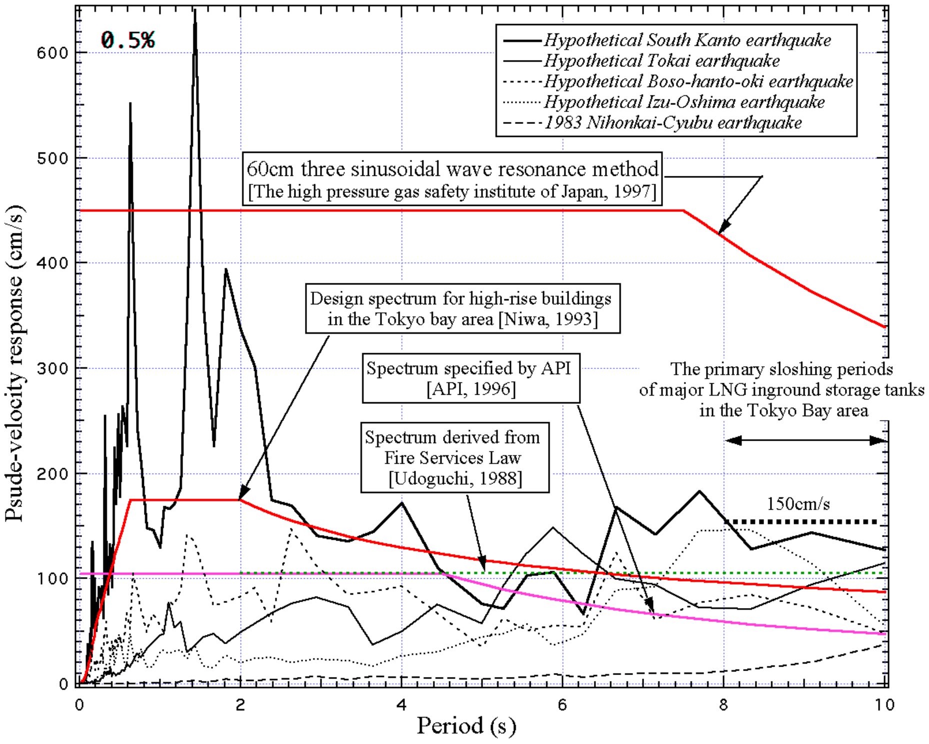


Figure 6: Characteristics of pseudo-velocity response spectra containing components with periods up to 10 seconds in the Tokyo Bay area (damping ratio is 0.5 %)

Also Figure 6 shows the envelopes of the pseudo-velocity response spectra from this analysis comparing with the following design spectra for ground motion considering periods up to 10 seconds:

a) the spectrum derived from the Earthquake-Proof Design Code for High-Pressure Gas Manufacturing Facilities [Subcommittee for Seismic Countermeasures of High-Pressure Gas and Explosives Security Council, 1980]; this was determined by the 60cm three sinusoidal wave resonance method and satisfied the High Pressure Gas Safety Law,

b) the spectrum derived from Fire Services Law [Udoguchi, 1988],

c) the spectrum specified by American Petroleum Institute [API, 1996], and

d) the spectrum of the standard earthquake ground motion for high-rise buildings in the Tokyo Bay area [Niwa, 1993].

For periods of 8 to 10 seconds, the envelopes from this study exceeded spectra from b), c), and d) above paragraph. Those spectra all were converted by a simplified formula into spectra of 0.5 % damping ratio. In addition, this analysis showed that the velocity response spectra obtained by 60cm three sinusoidal wave resonance method are about 2 to 3 times as intense as those assumed for the Tokyo Bay area for periods between 8 and 10 seconds.

CONCLUSION

Focus on typical sites of LNG inground storage tanks in the Tokyo Bay area, we evaluated the velocity response spectra based on the results obtained from the time history response analysis under past destructive earthquakes, and simulated earthquake ground motion including components with periods up to about 10 seconds. Results with past destructive earthquakes in section 2, together with the normal mode analysis in section 3, suggested that 180cm/s is an indicator of the velocity response spectrum value used to examine sloshing of inground storage tanks in Tokyo Bay area that have primary sloshing periods of 8 to 10 seconds. To summarize the results:

1. The time history response analysis of the sloshing from past destructive earthquakes showed that the velocity response spectrum value with a maximum near 180cm/s was significantly smaller than that based on 60cm three sinusoidal wave resonance method suggested by the High Pressure Gas Safety Law.
2. Of all pseudo-velocity response spectra simulated by semi-empirical method, only the hypothetical South Kanto earthquake's maximum envelope reached its maximum for periods between 8 and 10 seconds; this maximum was approximately 150cm/s. This range of resonant periods is typical of major LNG inground storage tanks in the Tokyo Bay area.
3. The authors found maximum envelopes of the pseudo-velocity response spectra greater or equal to those from previous studies about major velocity response spectra. In particular, the spectrum simulated by semi-empirical method for periods between 8 and 10 seconds were 2 to 3 times as intense as those obtained by 60cm three sinusoidal wave resonance method, a method suggested by the current High Pressure Gas Safety Law.

REFERENCES

API (1996), “Design and construction of large, welded, low-pressure storage tanks”, *API Standard 620, Ninth Edition*.

Aida, I. (1981), “Numerical experiments of historical tsunamis Generated off the coast of the Tokaido district”, *Bull. Earth. Res. Inst.*, University of Tokyo, 56(2), pp367-390 (in Japanese with English abstract)

Architectural Institute of Japan (1976), “Corrected waveforms of strong motion record (in the Tokachi-oki earthquake in 1968) at the Hachinohe port”, *Journal of Architecture and Building Science*, 91, 1107 (in Japanese).

Building Research Institute, Ministry of Construction (1965), “Niigata earthquake and damage to reinforced concrete buildings in Niigata city”, *Report of the Building Research Institute*, 42 (in Japanese).

Goto, H., Kameda, H., Sugito, M. and Imanishi, N. (1978), “Correction of SMAC-B2 accelerograph records by digital filter”, *Proceedings of the Japan Society of Civil Engineers*, 227, pp57-69 (in Japanese).

Inoue, R. (1986), “Studies on design earthquakes in the period of 2 to 20 sec –A review”, *Proceedings of the Japan Society of Civil Engineers, Structural Engineering/Earthquake Engineering*, 374/I-6, pp1-23 (in Japanese).

Ishibashi. K. (1981), “Specification of a soon-to-occur seismic faulting in the Tokai district, central Japan, based upon seismotectonics, *Maurice Ewing Series Vol.4, Am. Geophys. Union*, pp297-332.

Kanamori, H. (1971), “Faulting of the great Kanto earthquake of 1923 as revealed by seismological data”, *Bull. Earth. Res. Inst.*, University of Tokyo, 49, pp13-18.

Kudo, K. (1980), “A study on the contribution of surface waves to strong ground motions”, *Proc. 7th WCEE*, 2, Istanbul, pp499-506.

Kurata, E., Iai, S., Yokoyama, Y., and Tsuchida H. (1979), “Strong-motion earthquake records on the1978 Miyagi-ken-oki Earthquake in port areas”, *Technical Note of Port and Harbor Research Institute, Ministry of Transport, Japan*, 319.

Ministry of International Trade and Industry (1982), Notification No.23.

Nasu, S. and Morioka T. (1973), “Ground Motion in Violent Earthquakes (5)”, *The Kenchiku Gijutsu*, 267, pp241-247 (in Japanese).

Niwa, M. (1993), “Part 1: Input ground motion for aseismic design of high-rise buildings, (1) Standard Earthquake ground motion and Its Application”, *Kenchiku Bousai*, pp4-9.

Niwa, M., Ohbo, N., Suzuki, Y., and Nozawa, T. (1990), “Earthquake ground motion characteristics in Tokyo bay area – Part 1 Study on long period ground motion in records of the 1990.2.20 near Izu-Ohshima earthquake”, *Summaries of Technical Papers of Annual Meeting - Structures I*, Architectural Institute of Japan, pp347-348 (in Japanese).

Niwa, M., Yamanaka, H., Takemura, M., and Ikeura, T. (1993), “Earthquake ground motion characteristics in Tokyo bay area – Part 6 Study on long period ground motion during the Noto-hanto-oki earthquake on Feb.7, 1993”, *Summaries of Technical Papers of Annual Meeting - Structures I, Architectural Institute of Japan,* pp175-176 (in Japanese).

Noda, S. (1990), “Review and future prospect of prediction methods of long-period (2 – 20 sec) ground motions”, *Proceedings of the 18th Symposium on Ground Vibration, Architectural Institute of Japan,* pp45-54 (in Japanese with English abstract).

Okamoto, T. and Sakaki, N. (1984), “The Height of Sloshing wave-height of oil-tank at the time of Nihonkai-chubu earthquake”, *Proceedings of the 39th Annual conference of the Japan Society of Civil Engineers*, I-350, pp699-700 (in Japanese).

Simazaki, K. and Somerville, P. (1979), “Static and dynamic parameters of the Izu-Oshima, Japan, earthquake of January 14, 1978”, *Bull. Seism. Soc. Am.*, 69, pp1343-1378.

Takemura, M. and Ikeura, T. (1988), “A semi-empirical method using a hybrid of stochastic and deterministic fault models: simulation of strong ground motions during large earthquakes”, *J. Phys. Earth*, 36, pp89-106.

Tanaka, T., Yoshizawa, S., and Osawa, Y. (1979), “Characteristics of Strong Earthquake Ground Motion in the Period Range from 1 to 15 Seconds”, *Bull. Earth. Res. Inst.*, University of Tokyo, 54, pp629-655 (in Japanese with English abstract).

The High Pressure Gas Safety Institute of Japan (1997), “Earthquake-proof design code for high-pressure gas manufacturing facilities”, *The High Pressure Gas Safety Institute of Japan*.

The Japan Gas Association (1981), “Recommended practice for LNG above ground storage”, *The Japan Gas Association*.

Udoguchi, T. (1988), “On the guideline for seismic design of oil storage steel tanks included in JIS B 8501 – 1985 Welded steel tanks for oil storage”, *Journal of High Pressure Institute of Japan*, 26, 5, pp47-55 (in Japanese with English abstract).

Zama, S. (1990), “Predominant periods of long period ground motion”, *Report of Fire Research Institute of Japan*, 70, pp1-7 (in Japanese with English abstract).

Zama, S. (1991), “A study on the regional differences in the characteristics of long-period strong ground motions observed by JMA strong motion seismograph (Part 1)”, *Report of Fire Research Institute of Japan*, 72, pp11-23 (in Japanese with English abstract).

Zama, S. (1993), “Characteristics of long-period strong ground motions observed by JMA strong motion seismograph (Part 2: Tokyo)”, *Report of Fire Research Institute of Japan*, 76, pp1-11 (in Japanese with English abstract).

Zama, S. (1993), “Long-period strong ground motion”, *ZISIN*, 46, pp329-342 (in Japanese).

Zama, S. and Inoue, R. (1994), “Sloshing of liquid in oil storage tanks due to the 1993 Hokkaido Nansei-oki earthquake”, *Report of Fire Research Institute of Japan*, 77, pp1-10 (in Japanese with English abstract).