13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 394

EARTHQUAKE RESPONSE ANALYSIS OF LNG STORAGE TANK BY AXISYMMETRIC FINITE ELEMENT MODEL AND COMPARISON TO THE RESULTS OF THE SIMPLE MODEL

Byeong Moo JIN[1], Se Jin JEON[2], Seong Woon KIM[3], Young Jin KIM[4], Chul Hun CHUNG[5]

SUMMARY

Simple beam-stick models are widely used for seismic analysis or design of structures. For the liquid storage tank, the tank structure and the liquid are modeled as lumped parameters, such as springs and masses. However, response spectrum analysis with these simple models, it would be possible that the results might give somewhat differences in section forces of shell structures such as the LNG (Liquid Natural Gas) storage tank, where especially the roof structure exists. Also the sloshing height could be underestimated when it is considered only one sloshing mode.

Therefore, axisymmetric finite elements were employed to model the LNG storage tank in present study. The general purpose FE analysis program, ANSYS was utilized to model the LNG liquid, the inner steel tank and the outer concrete tank consisting of LNG storage tank. Modal analysis result shows that the axisymmetric finite element model of LNG tank considering FSI (fluid-structure interaction) effect is quite adequate. The response spectrum analysis was conducted on axisymmetric finite element model of LNG storage tank. And the results were discussed comparing with simple model. Finally full dynamic analyses in time domain were performed to examine the validity of the results.

It is concluded that the response spectrum analysis of axisymmetric finite element considering FSI would result in more accurate seismic design of LNG storage tank than the simple model and be more practical than the full dynamic analysis.

INTRODUCTION

Generally the lumped beam-stick models have been used for the structural analysis of axisymmetric cylindrical structure such as LNG storage tanks, nuclear power containment vessels. The global structural responses of the structure subjected to dynamic loads such as earthquakes have been calculated by these

[1] Senior Researcher, DAEWOO E&C Co. Ltd., Korea. Email: jinbm@dwconst.co.kr
[2] Senior Researcher, DAEWOO E&C Co. Ltd., Korea. Email: jsj@dwconst.co.kr
[3] Research Fellow, DAEWOO E&C Co. Ltd., Korea. Email: swk@dwconst.co.kr
[4] Chief Researcher, DAEWOO E&C Co. Ltd., Korea. Email: kimyj@dwconst.co.kr
[5] Professor, Dankook University, Korea. Email: chchung5@dankook.ac.kr

lumped beam-stick models which are reasonable methods as a preliminary analysis for the detailed finite element analysis. The dynamic responses such as displacement, accelerations computed by detailed finite element analysis are regarded as very similar to those by simple lumped model. However the sectional force distributions of realistic structure showed somewhat different to the simple beam-stick model. Though the sectional force differences may not be the important factor to the design of total structures, nowadays it is said that the detailed finite element analysis are necessary part. And it requires many experiences and cautions for the engineers to analyze and design a structure by using a simple model.

The effects of inner liquid in seismic design of liquid storage tanks such as LNG tank were considered as lumped parameters. (Haroun and Housner[1,2]; Haroun[3]). The inner liquids were modeled as the lumped mass and spring of impulsive part and convective part respectively, and were coupled to the lumped parameter model (or simple beam-stick model) of the storage tank structure. This method shows identical results with the detailed finite shell element analysis when the tank has uniform thickness. However if the thickness of wall is not uniform or the roof structure such as dome in LNG storage tank exists, the simple approach has some different results. In this study, both finite element model and lumped mass and spring model of the LNG storage tank are used.

SIMPLE ANALSYS: CYLINDRIAL CANTILEVER RESPONSES

To compare the behaviors of beam-stick and axisymmetric shell model, simple dynamic analysis of cylindrical cantilever with same flexural rigidity and mass has been carried out. The cantilever is modeled as a simple beam with shear deformation and 6 shell models, which have same moment inertia (Figure 1).

The simple beam model has moment inertia *I,* and shell model has thickness *t* and diameter *D*=2*R* with the relationship $I = \pi R^3 t$. The excitation force is one period sine-wave with amplitude unit 1.

In Figure 2-Figure 4, the horizontal displacements, base shear forces and overturning moments are presented for $D \le 24$. Also those for $D \ge 48$ are presented in Figure 5-Figure 7. From the results, the displacement, base shear force and overturning moment time histories are very similar to those of simple beam model and 3 shell models with $D \le 24$. However, in the case of $D \ge 48$, the shell responses are very different with the beam response particularly in horizontal displacement. Naturally, the storage structures with extreme ratio of $t / D \le 10^{-5}$ are not realistic and no one will model these structures simply with beam-stick model. However, this example shows that the simple model and the shell model (finite element model) may have differences in results.

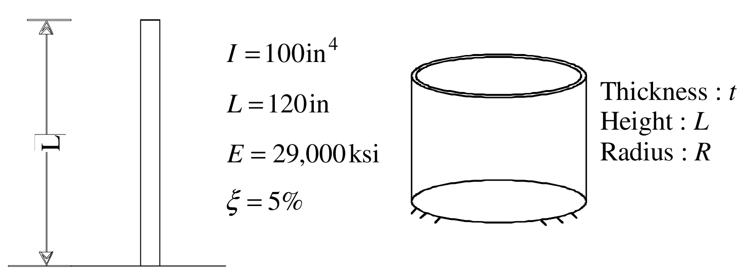


Figure 1: Cantilever model for comparison

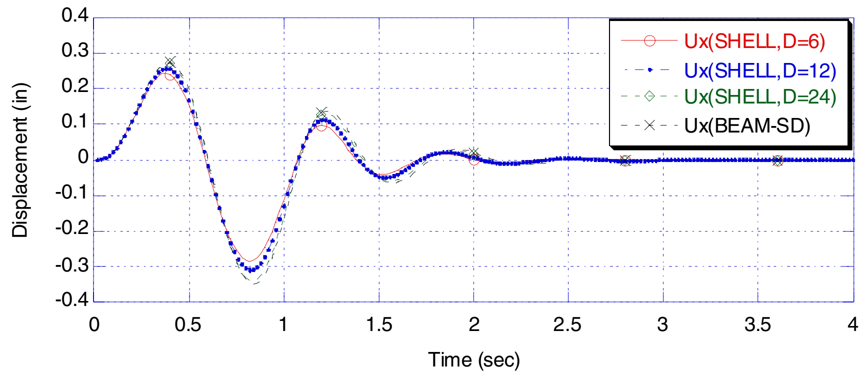


Figure 2: Displacement time histories (D=6, 12, 24)

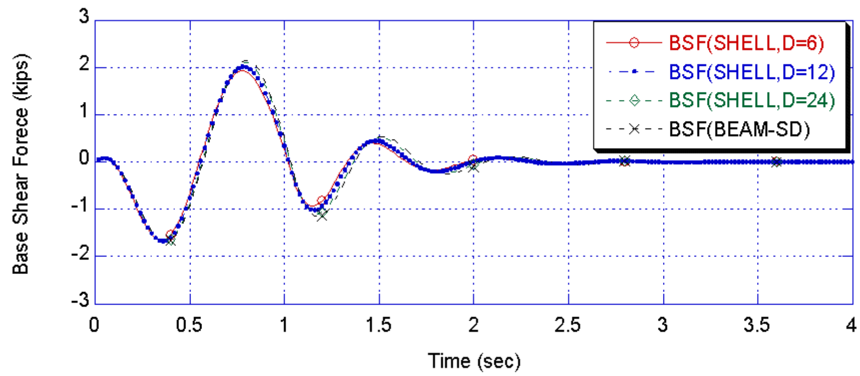


Figure 3: Base shear force (BSF) time histories (D=6, 12, 24)

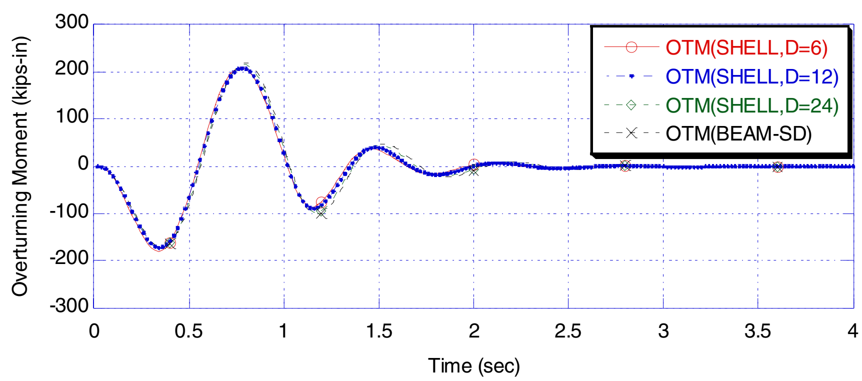


Figure 4: Overturning moment (OTM) time histories (D=6, 12, 24)

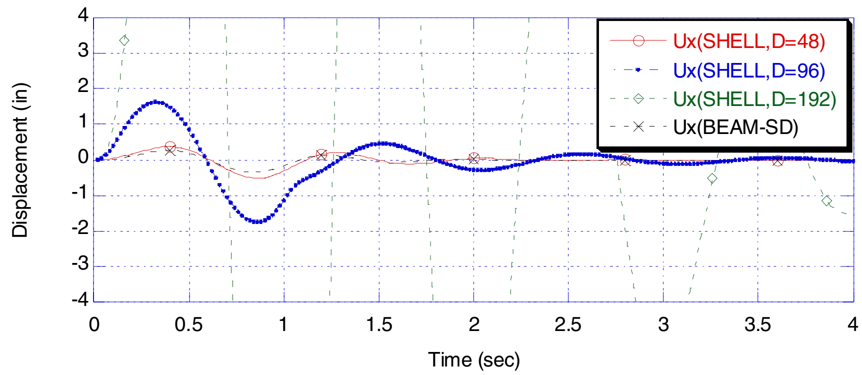


Figure 5: Displacement time histories (D=48, 96, 192)

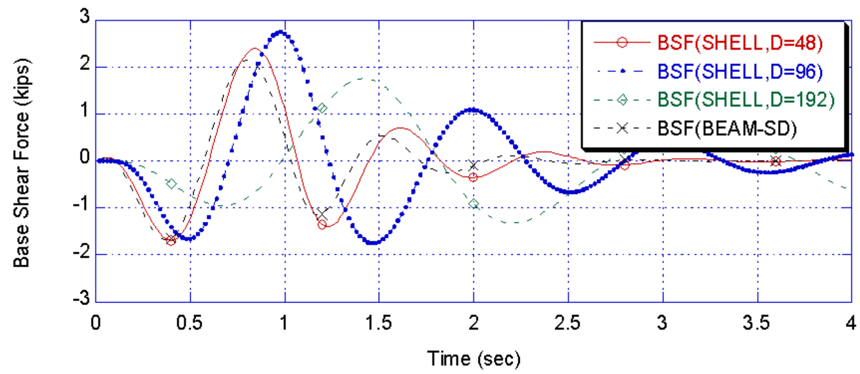


Figure 6: Base shear force (BSF) time histories (D=48, 96, 192)

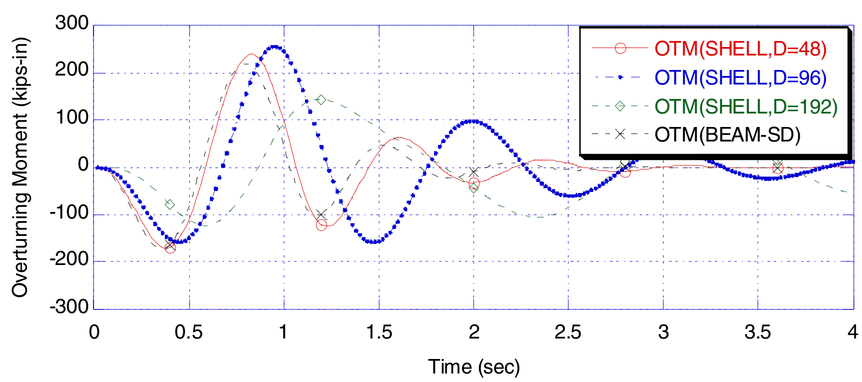


Figure 7: Overturning moment (OTM) time histories (D=48, 96, 192)

APPLICATION: MODAL ANALYSIS OF BROAD & TALL WATER TANK

For one application, authors choose water storage tanks with the ratios of H/R=3 (tall tank) and 2/3 (broad tank) [3]. The structural properties are listed in Table 1. The tanks are modeled as simple beams with lumped parameter liquid mass-spring and axisymmetric finite shell with finite fluid element model . Figure 8 shows the structural modeling of water storage tank.

The structural models for tanks are two beam models and two shell models shown in Figure 9. The case A represents that the tanks are modeled as shear beam with shear factor 2; case B for shear factor proposed by TID [4]; case C for shell model without stiffener ring; case D for shell model which is stiffened with stiffener ring.

The modal analysis results are summarized in Table 2 and 3 for the case of sole tanks without inner liquid and tanks with inner liquid respectively. From Table 2, beam model with shear factor 2 (case A) and shell model with stiffener ring (case D) are quite similar for both tall and broad tank. For the case of tall tank, the beam model (case A & B) results show good agreement with the results of the shell model (case C, D and Haroun[3]) in both structural fundamental frequencies and sloshing frequencies.

However for the case of broad tank, the structural fundamental frequencies are 45.0Hz for case A and case D, which means the structural behaviors of stiffened shell are very similar to that of shear beam model with shear factor=2 (case A). The broad tank without stiffened ring (case C) has fundamental frequencies of 33.99, 43.76 and 44.38 Hz, which are less than those of shear beam model (case A) and very contiguous to the first frequency. The ratio t/D of broad tank is 6.93×10^{-4}, one can assume that the deformation in a section would be more dominant than the horizontal rigid motion. The 1st fluid-structure interaction frequencies for case C and Haroun[3] are very similar. And the fluid-structure interaction frequencies for case A and case D are quite similar, so the fluid-structure interaction behaviors of stiffened shell model are quite similar to those of shear beam model for these cases.

Table 1: Properties of liquid storage tank

	Tall tank	Broad tank
Radius R	7.32 m	18.3 m
Height H	21.96 m	12.2 m
Thickness t	2.54 cm	
Liquid Density ρ_l	1000 kg/m^3	
Structure Density ρ_s	7840 kg/m^3	
Poisson's ratio ν	0.3	
Young's Modulus E	206.7 GPa	
t / D	0.0017	0.00069

Table 2: Fundamental frequencies without inner liquid (unit: Hz)

Mode	Tall tank				Broad tank			
	Beam Case A	Beam Case B	Shell Case C	Shell Case D	Beam Case A	Beam Case B	Shell Case C	Shell Case D
1	19.46	18.54	19.17	19.87	45.30	23.031	33.99	45.00
2	55.90	53.23	56.00	56.97	104.98	71.99	43.76	109.56
3	98.37	92.10	85.79	99.19	141.14	105.24	44.38	141.09

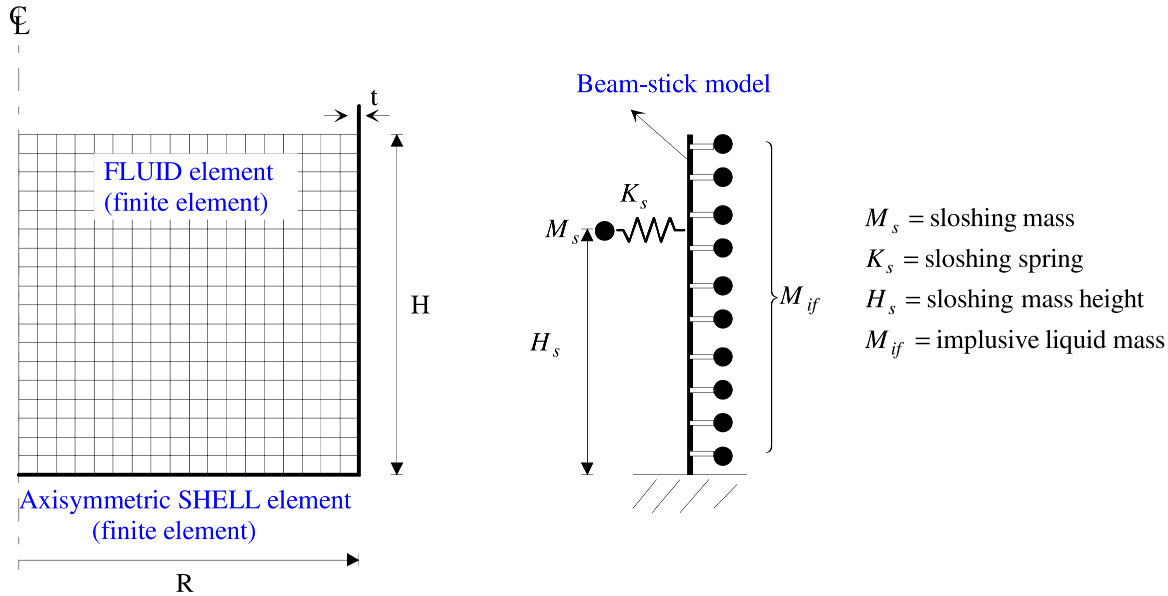
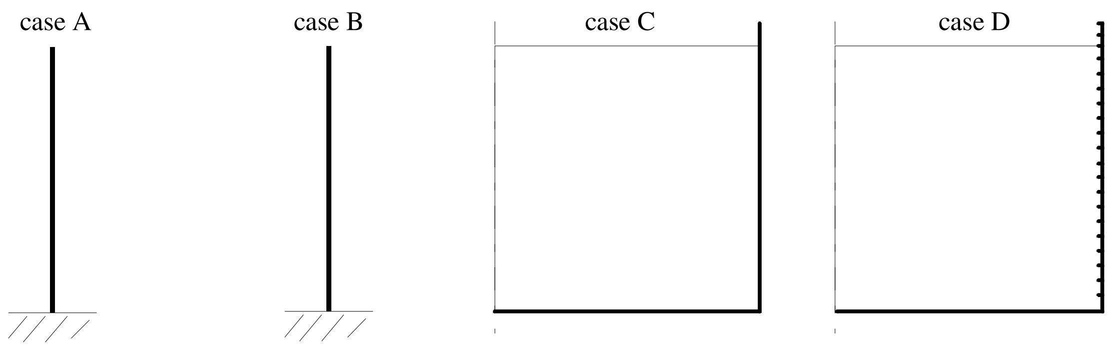


Figure 8: axisymmetric FSI model and simple FSI model



(a) Shear factor=2 (b) Shear factor by Ref[4] (c) Shell w/o stiffener ring (d) Shell with stiffener ring

Figure 9: Structural models of water storage tanks

Table 3: Fundamental frequency with inner liquid (unit: Hz)

Mode	Tall tank					Broad tank				
	Beam Case A	Beam Case B	Shell Case C	Shell Case D	Haroun[3]	Beam Case A	Beam Case B	Shell Case C	Shell Case D	Haroun[3]
sloshing	.2495	.2495	.2494	.2494	.2499	.145	.145	.145	.145	.1448
FSI 1	5.92	5.58	5.27	5.658	5.292	12.38	6.53	6.123	12.11	6.173
FSI 2	16.63	15.58	15.23	18.75	-	34.30	18.12	11.21	39.30	-
FSI 3	30.39	28.13	22.43	38.64	-	56.49	29.66	15.10	60.07	-

APPLICATION: 200,000 KL LARGE LNG STORAGE TANK

200,000 kl large LNG storage tank

Figure 10 shows the schematic view of basic design section of the 200,000kl LNG storage tank under development by DAEWOO E&C Co., LTD. The maximum operation level (H.L) and maximum design level (H.H.L) of LNG is 33.554 m and 33.864m respectively. The diameters of inner tank and outer tank are 90.0m and 92.0m respectively. The diameter of the 200,000kl LNG storage tank is 6.0m larger than 140,000kl tanks constructed or being constructed at Tongyoung, Korea. Basic design section has been determined by main loadings which should be considered in design. Works on the final design section due to these loadings are in progress and works on seismic design or analysis also being accomplished as a part of these works.

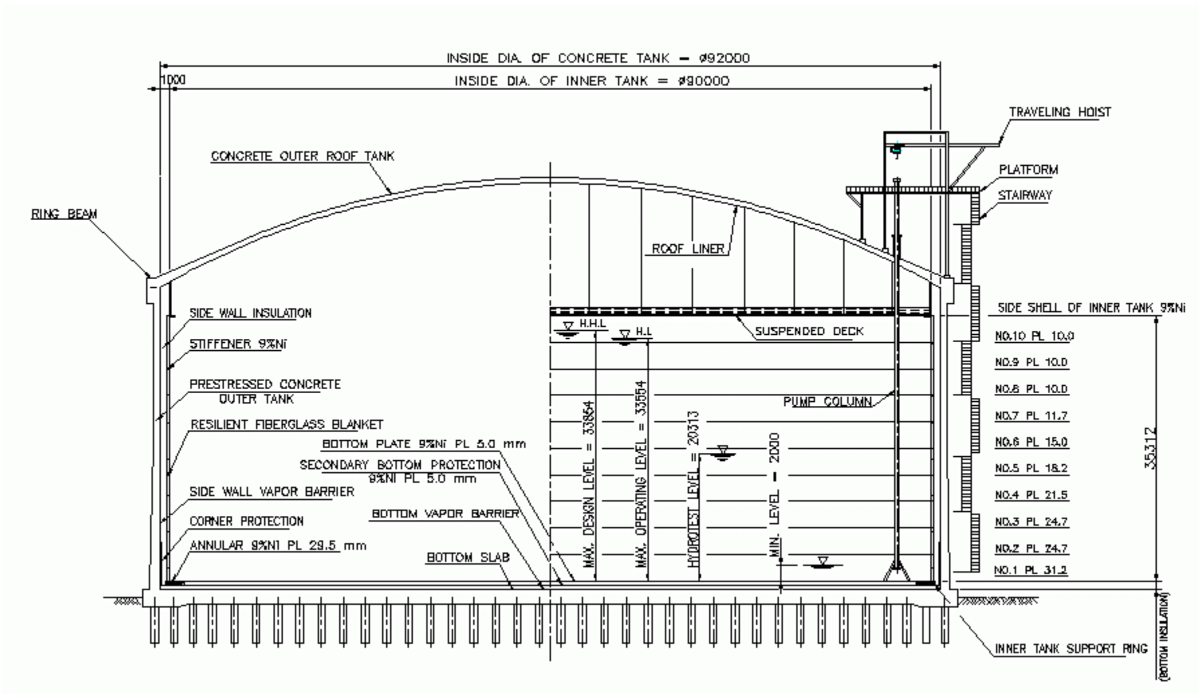


Figure 10: Schematic view of basic design section of the 200,000kl Large LNG storage tank

Table 4: Material Properties of LNG Storage Tank

		Density (kgf/m^3)	Young's Modulus (GPa)	Poisson's Ratio
LNG		480	-	-
9% Ni inner steel tank		7850	208	0.2
Perlite concrete		2500	2.6	0.17
Outer concrete tank	Roof	2450	26	0.17
	Wall	2500	28	0.17
	Bottom slab	2450	26	0.17

Modeling of 9% Ni inner steel tank & pre-stressed concrete (PSC) outer tank

The 9% Ni inner steel tank wall will be stiffened by stiffener ring to avoid the local buckling. Therefore, the inner steel tank is modeled as beam model considering shear deformation (in this case, the shear factor used for the inner tank is 2). To meet the fundamental frequencies and modes of shear-beam model, the axisymmetric finite shell model must be constrained ($\bar{u} + \bar{v} = 0$). However, unfortunately the realistic effect of stiffener ring were not investigated thoroughly, the shell model without stiffening ring is adopted.

The pre-stressed concrete outer tank is also modeled as beam-stick model considering shear deformation, and axisymmetric shell model. Table 4 shows the material properties for modeling 200,000kl LNG tank. Figure 11 shows the axisymmetric finite element model of 200,000kl LNG tank. The detailed modeling procedures are not presented here.

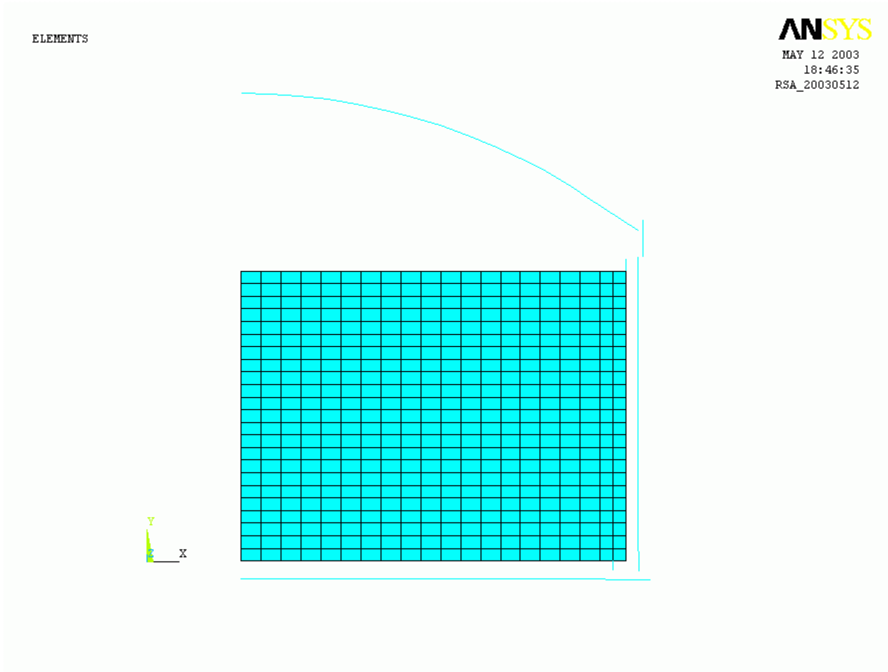


Figure 11: Axisymmetric model of LNG storage tank

Modal analysis result of axisymmetric finite element model

Sloshing modes

The fundamental frequencies and the fundamental modes are very important in performing the dynamic analysis and understanding the results. The fundamental periods of LNG liquid sloshing can be calculated from theoretical sloshing frequencies.

$$T_n = \frac{1}{f_n} \text{ (n-th fundamental period) or } f_n = \frac{1}{2\pi}\sqrt{\frac{g}{R}\varepsilon_n \tanh\left(\varepsilon_n \frac{H}{R}\right)} \text{ (n-th fundamental frequency)}$$

where, f_n : n-th fundamental frequency, g : Acceleration of gravity (9.81m/sec^2)
R : Radius of liquid storage tank, H : Height of liquid level from bottom
ε_n : n-th solution of Bessel function $J(\varepsilon)$ (Refer to Table 5)

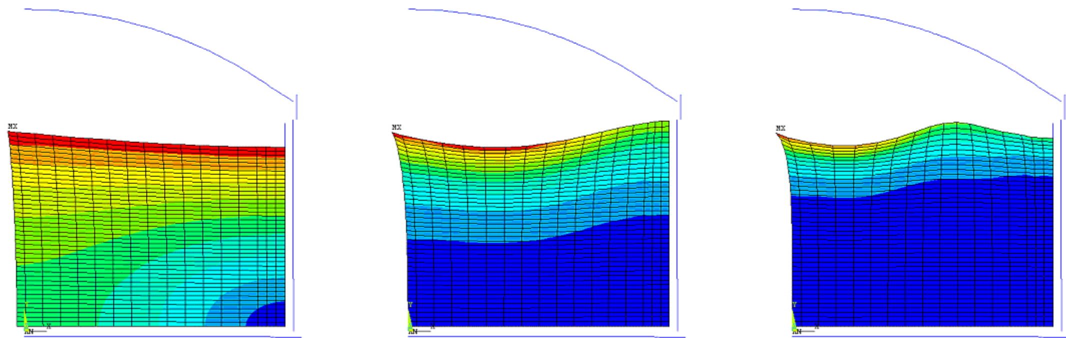
Table 5: Solutions of Bessel function $J(\varepsilon)$

n	1	2	3	4	5
ε_n	1.841	5.331	8.536	11.706	14.863

Figure 12 shows the sloshing modes of inner LNG liquid. The 1st fundamental frequency of sloshing motion is computed as 0.0945Hz, which is nearly identical to the theoretical one. Table 6 summarizes the fundamental sloshing frequencies. From the similarity of the sloshing frequencies computed by ANSYS and those by analytical method in Table 6, it is concluded that the usage of fluid elements of ANSYS is very acceptable.

Table 6: Sloshing frequencies (unit: Hz)

Sloshing mode No.	Theoretical	This study
1	0.0947	0.0945
2	0.1745	0.1732
3	0.2171	0.2234
4	0.2542	0.2687
5	0.2865	0.3131



(a) 1st mode (0.095Hz) (b) 2nd mode (0.173Hz) (c) 3rd mode (0.223Hz)

Figure 12: Sloshing modes for the 200,000kl LNG tank

Interaction modes

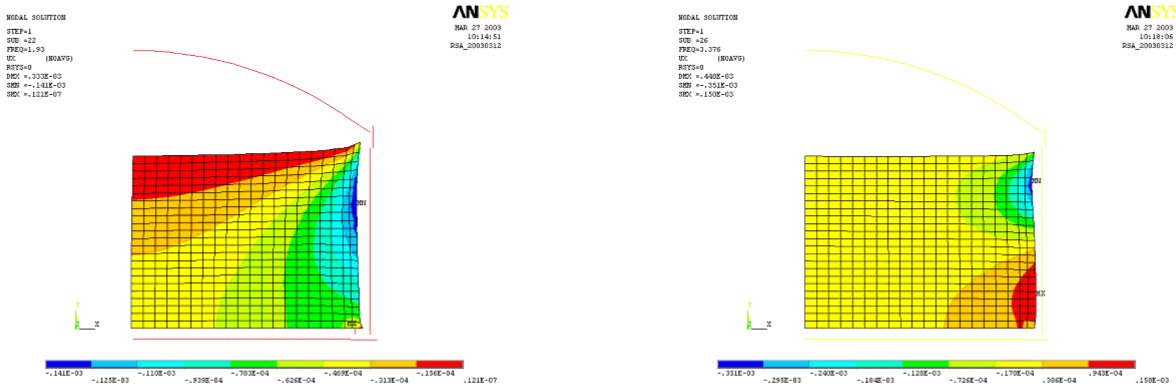
The interaction modes are caused by the flexibility of tank structure and the dynamic pressure applied by inner liquid. The fluid-structure interaction modes are shown in Figure 13. The natural frequency of inner steel tank is more than 14.0Hz (14.07Hz for the tank w/o stiffener ring and 19.46Hz for the tank with stiffener ring). The 1st interaction frequency is computed as 1.93Hz and the deformation mode is shown in Figure 13a. The maximum relative displacement of inner steel tank occurs at the wall middle.

In this study, it is assumed that the insulation materials between inner steel tank and outer concrete tank have no stiffness. Therefore, the outer tank behaves solely without interaction with the inner tank or inner LNG liquid. The first fundamental horizontal deformation mode of the outer tank is shown in Figure 14 and the natural frequency of the outer tank is computed as 4.953Hz, which is the same as the result of outer tank modal analysis. Table 7 summarizes the fundamental frequencies of inner LNG liquid sloshing motion or convective motion, the interaction frequencies (impulsive motion), and the fundamental frequencies of outer tank.

Table 7: Fundamental frequencies of 200,000kl LNG tank (axisymmetric FE model)

Mode	Freq.	Mode	Freq	Mode	Freq.	Mode	Freq.	Mode	Freq
1	0.0945	11	0.5762	21	1.412	**31**	4.466	**41**	7.263
2	0.1723	12	0.6403	**22**	1.930	**32**	4.839	**42**	7.395
3	0.2205	13	0.7125	**23**	2.968	**33**	4.953	**43**	7.601
4	0.2624	14	0.7925	**24**	3.062	**34**	5.312	**44**	7.991
5	0.3020	15	0.8789	**25**	3.214	**35**	5.367	**45**	8.248
6	0.3412	16	0.9686	**26**	3.376	**36**	5.989	**46**	8.664
7	0.3813	17	1.060	**27**	3.423	**37**	6.046	**47**	8.651
8	0.4234	18	1.154	**28**	3.687	**38**	6.705	**48**	9.226
9	0.4690	19	1.247	**29**	4.008	**39**	6.721	**49**	9.873
10	0.5194	20	1.320	**30**	4.390	**40**	6.724	**50**	9.908

1 – 21st modes: sloshing modes, **22 – 50th**: interaction modes except 33, 39, 41 and 45th modes
33, 39, 41 and 45th mode: outer tank deformation modes



(a) 1st mode (1.93Hz) (b) 2nd mode (3.38Hz)

Figure 13: Fluid-structure interaction modes for the 200,000kl LNG tank

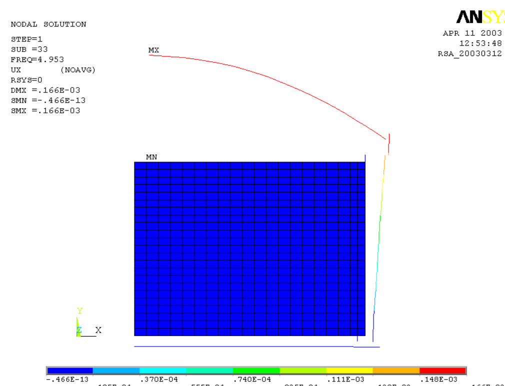


Figure 14: Outer PSC tank deformation mode of the 200,000kl LNG tank (1st mode, 4.95Hz)

Response spectrum analysis result of axisymmetric finite element model

The design response spectrum used for RSA is modified NRG spectrum with the PGA=0.02g as shown in Figure 15.

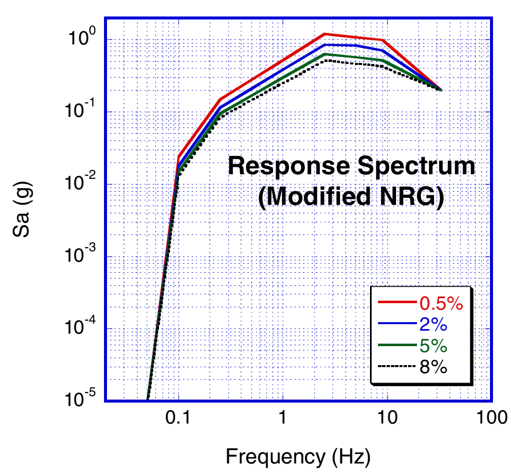


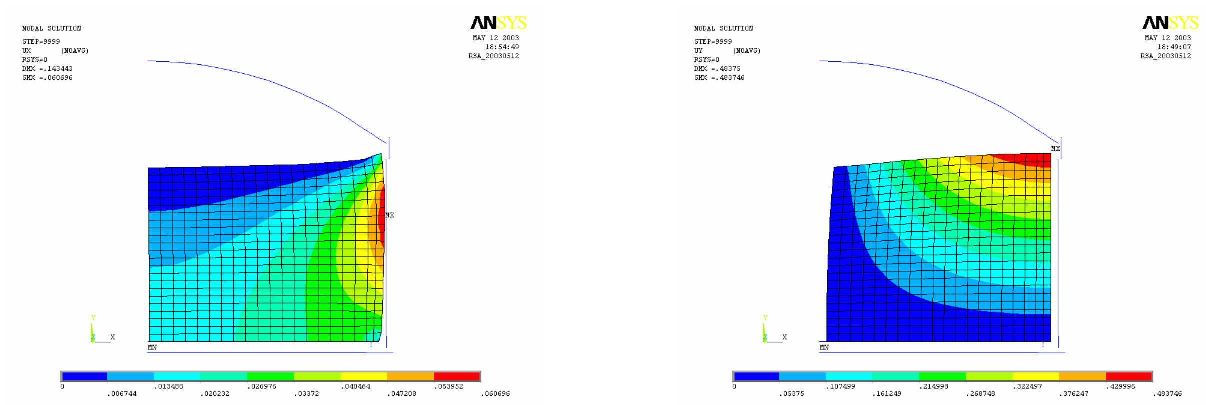
Figure 15: Design response spectrum (modified NRG)

The maximum deformation of inner tank is approximately 60.7mm shown in Figure 16a. The maximum deformation of outer tank is approximately 11mm (for 2% damping) and shown in Figure 17a. For the 5% damping ratio, the maximum deformation of outer tank is approximately 7.5mm and shown in Figure 17b. The maximum sloshing height is about 48.37cm shown in Figure 16b. The exact sloshing height (considering the 1st sloshing mode) can be estimated from following equation.

$$\eta = 0.837R\frac{S_a}{g} \quad (\eta : \text{sloshing height})$$

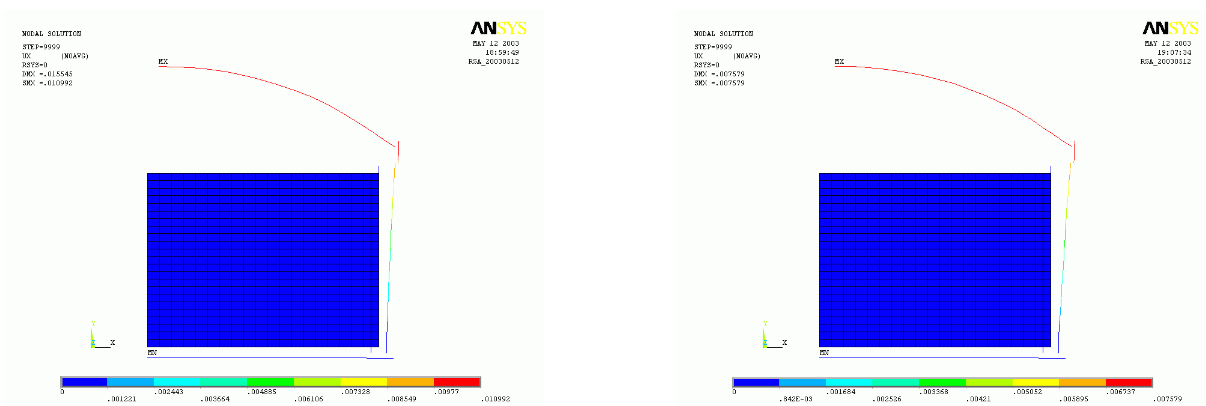
The spectral acceleration, $S_a = 0.12485(\text{m/sec}^2)$ can be found from response spectrum (Figure 15) at the first sloshing frequency, then the sloshing height considering the 1st mode is

$$\eta = 0.837 \times 45 \times \frac{0.1248}{9.81} = 0.4792m = 47.92cm$$



(a) inner tank deformation (b) sloshing motion

Figure 16: Maximum deformation mode of inner steel tank and sloshing mode



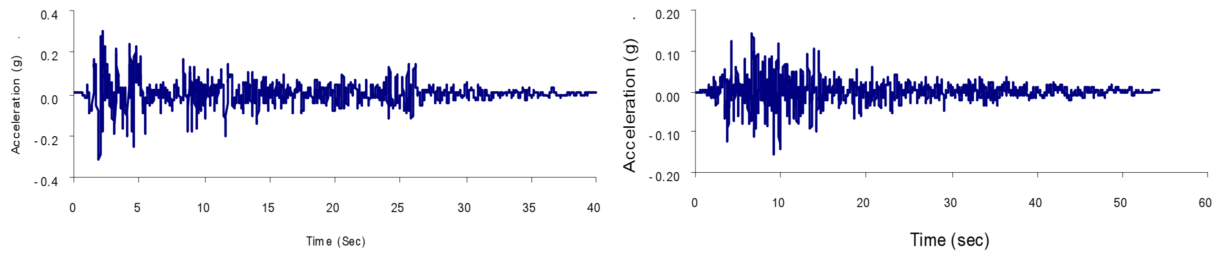
(a) 2% damping (b) 5% damping

Figure 17: Maximum deformation mode of outer tank

Time history analysis result of axisymmetric finite element model

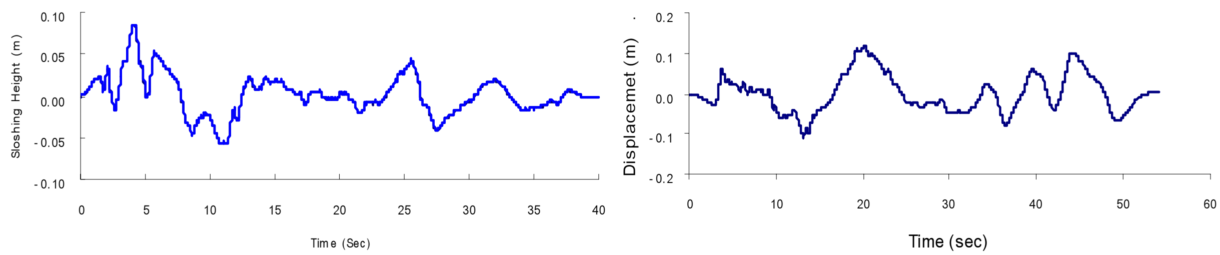
For the time history analyses, two earthquake motions are employed as input motion normalized to PGA=0.02g. The ground acceleration time histories used for input motions are 1940 El Centro Imperial valley earthquake NS component (maximum PGA = 0.31g) and 1952 Taft Kern county earthquake 021 component (maximum PGA = 0.15g).

Figure 18 shows the ground acceleration time histories and Figure 19 shows the displacement time histories corresponding to normalized acceleration to 0.2g. The peak ground accelerations for each earthquake is normalized to 0.2g for the comparison with response spectrum analysis results.



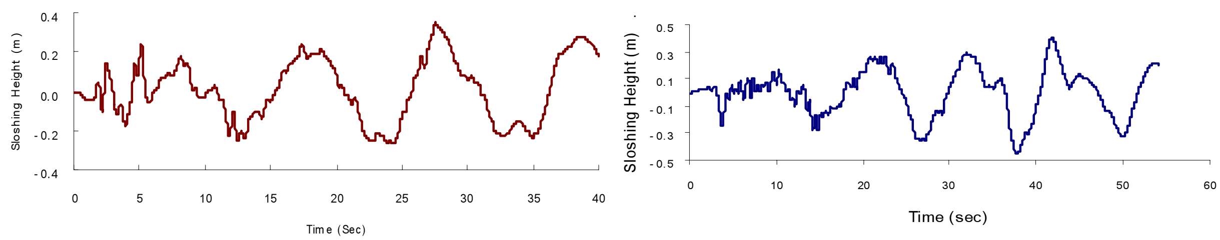
(a) 1940 El Centro earthquake (b) 1952 Taft earthquake

Figure 18: Acceleration time histories (input motions)



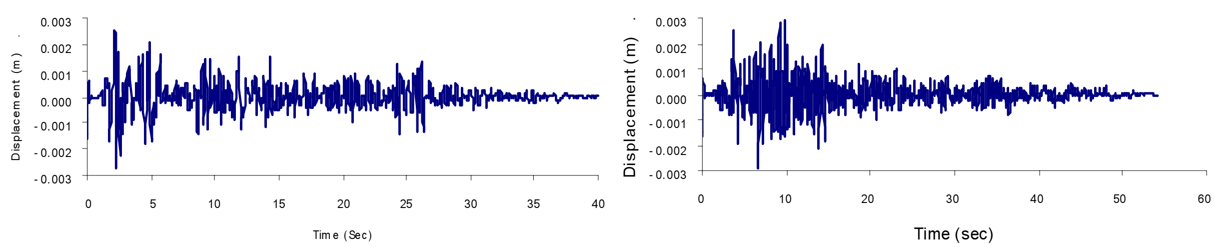
(a) 1940 El Centro earthquake (b) 1952 Taft earthquake

Figure 19: Displacement time history corresponding to normalized acceleration to 0.2g



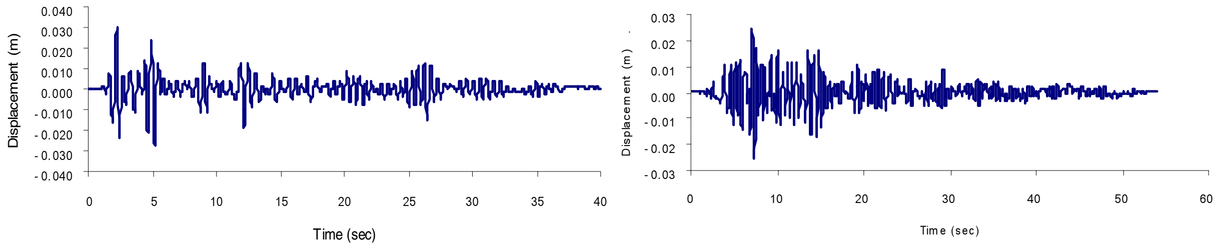
(a) 1940 El Centro earthquake (b) 1952 Taft earthquake

Figure 20: Sloshing motions



(a) 1940 El Centro earthquake (b) 1952 Taft earthquake

Figure 21: Relative displacement time histories of outer tank



(a) 1940 El Centro earthquake (b) 1952 Taft earthquake

Figure 22: Relative displacement time histories of inner tank

For El Centro earthquake input motion, the maximum sloshing height of time history analysis is 0.34m as shown in Figure 20a, while that of response spectrum analysis is 0.48m. The maximum relative displacements of inner tank and outer tank(at the 2/3 height of inner tank wall and the roof respectively) for time history analysis are 0.003m and 0.03m as shown in Figure 21a and Figure 22a, while those of response spectrum analysis are 0.0075m and 0.06m

Table 8 summarizes the results of a response spectrum analysis and two time history analyses. The peak ground acceleration (PGA) was normalized to SSE with 0.2g. The sloshing height from response spectrum is calculated as 0.48m, while time history analyses results are 0.38m and 0.45m for El Centro earthquake and Taft earthquake respectively. The outer tank deformation is 7.5mm for response spectrum, while the time history results are 3mm for both earthquake motions. The inner tank deformation is calculated as 6cm for response spectrum analysis and the time history results are 3cm and 2.5cm respectively. In general, the response spectrums of SDOF system are the possible maximum displacement, velocity or acceleration for given specific earthquake motion, and the design spectrum is envelope of these response spectrums. Therefore, the maximum values for response spectrum analysis are larger than those of time history analysis. Thus the results in Table 8 are thought to be reasonable.

Table 8: Results of response spectrum analysis and two time history analyses

	RSA	1942 El Centro EQ	1952 Taft EQ
PGA (g)	0.2g	0.2	0.2
Sloshing height (cm)	48 cm (mode 1)	38	45
Outer tank deformation (mm)	7.5 mm	3	3
Inner tank deformation (cm)	6 cm	3	2.5

Comparison of dynamic characteristics of shell mode and simple beam model

Finally Table 9 summarized the modal analysis results of various shell models and shear beam model. For inner steel tank, the fundamental frequencies and modes of shear beam model are corresponding to those of shell with stiffener ring. However if the tank wall were not stiffened sufficiently, the 1st natural frequency of tank would be 14.0 Hz to 19.4 Hz. The dynamic characteristics of sole inner tank, i.e. without inner LNG liquid, may not be changed greatly, but the fluid-structure interaction frequency of the inner tank would be 1.9 Hz to 3.9 Hz. This means that the first interaction frequency would be about 2 times of the tank without stiffener ring.

For outer PSC tank, the 1st fundamental frequency of shear beam and rigid stick model is 5.38Hz, while that of shell model without stiffener ring, which is more alike to the realistic PSC tank, is 4.95Hz. Also the modes 39, 41 and 45 listed in Table 7 are roof deformation modes which can be considered in shear beam and rigid stick model.

The response spectrum analysis result of 200,000kl LNG tank is shown in Table 10. The sloshing heights are merely computed by RSA for both shear beam model and axisymmetric FE model. Even though the sloshing height can be calculated from theoretical formula or code with spectral acceleration and radius of liquid tank, the results done by simple beam model RSA is underestimating the sloshing height. However, the sloshing height considering only one mode by axisymmetric FE model RSA is quite identical to theoretical sloshing height. If there is need to compute more accurate sloshing height, more sloshing modes have to be included in RSA. The inner or outer tank deformations of shear beam model and axisymmetric finite element model seems to be quite different. This may be caused by the fundamental frequency differences (3.62 Hz for beam model vs. 1.93 Hz for shell model).

Table 9: Fundamental frequencies of 200,000kl LNG tank (unit: Hz)

	Inner steel tank						Outer PSC tank		
	Beam		Shell w/ stiffener		Shell w/o stiffener		Beam	Shell	
Mode	No LNG	FSI	No LNG	FSI	No LNG	FSI		w/o stiff.	w/ stiff.
Sloshing	-	.0945	-	.0946	-		-	-	-
1	19.34	3.62	19.46	3.94	1.93	14.07	5.38	4.95	5.20
2	43.16	9.00	41.50	13.04	3.38	17.33	18.17	10.75	15.24
3	74.30	14.31	79.93	22.03	-	17.65	22.98	12.20	26.94

Table 10: Response spectrum analysis results of 200,000kl LNG tank

	Shear Beam model	Axisym. FE model
PGA (g)	0.2g	0.2
Sloshing height (cm)	38 cm*	48 cm
Outer tank deformation (mm)	5.4 mm	7.5 mm
Inner tank deformation (cm)	2.2 cm	6 cm

CONCLUSIONS

In this study, earthquake response analysis of LNG storage tank has been conducted by axisymmetric finite element model (with axisymmetric shell and fluid element). Typically the LNG storage structure is a cylindrical tank, so shear beam model has been used for seismic analysis or design as done in seismic design of liquid storage tank. However the inner tank and outer tank consisting of LNG storage structure have usually varied thickness in wall, also the PSC outer tank has a dome type roof structure above the ring-beam, which is usually modeled as a rigid stick in beam model. Therefore the dynamic behaviors differences have been shown in the modeling scheme between shell model and beam model. And it has been shown that the dynamic characteristics of fluid-structure interaction system are different with the modeling methods of the lumped parameter liquid model, i.e., mass-spring and axisymmetric fluid element. The simple model is more effective and time-saving to understand the over-all behaviors of liquid storage tank; one must keep in mind that the simple model is an ideal model and should utilize the simple model as a preliminary analysis. As the detailed FE analysis procedures require more time and efforts, one must keep paces with the simple model to reduce the trial-and-error as much as possible.

REFERENCES

1. Haroun, M.A., Housner, G.W., (1981), "Seismic Design of Liquid Storage Tanks", *Journal of the Technical Council of ASCE*. pp.747-763.
2. Haroun, M.A., Housner, G.W., (1981), "Earthquake Response of Deformable Liquid Storage Tanks", *Journal of Mechanics, ASME*, Vol.48. pp.411-418.
3. Haroun, M.A. (1983), "Vibration Studies and Test of Liquid Storage Tanks", *Earthquake Engineering and Structural Dynamics*, Vol.11. pp.179-206.
4. TID-7024, U.S., "*Nuclear Reactors and Earthquakes*", Chapter 6, Dynamic Pressure on Fluid Containers, Atlantic Energy Commission Publication.