Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Some Suggestions for Sloshing Response Analysis in Liquid Storage Tanks Subjected to Earthquake Ground Motions

Young-Sun Choun
Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Daejeon, 305-353, Republic of Korea
E-mail: sunchun@kaeri.re.kr

1. Introduction

The sloshing behavior of a tank is very sensitive to the characteristics of input motions, as well as the configuration of the tank-liquid system. Nevertheless, most of the past studies focused only on the configuration of tanks and the dynamic properties of the fluid motion. Therefore, the sloshing response in liquid storage tanks for earthquake excitation has not been properly predicted in many cases until now.

As one useful parameter to characterize the significant frequency content of input earthquake motions, the peak ground acceleration to velocity (A/V) ratio is utilized. The ground motions, exhibiting a large amplitude, and very high frequency content in the strong-motion phase, generally result in high A/V ratios and very large spectral acceleration values in short periods, whereas the ground motions, containing intense, long-duration acceleration pulses, would generally lead to low A/V ratios and pronounced spectral acceleration values for a moderate or long period. Normal ground motions with significant energy content over a broad range of frequencies and exhibiting a highly irregular acceleration pattern would generally have medium A/V ratios and acceleration spectra similar to the standard design spectrum [1].

In this study, the sloshing response in rigid rectangular tanks subjected to various earthquake ground motions with different peak A/V ratios is investigated.

2. Sloshing Analysis

2.1 Analysis Method

A two-dimensional, partially liquid-filled rigid rectangular tank having a length L and a liquid depth d is considered. The main assumptions of the tank-liquid system are (a) the tank is assumed to be rigid; (b) the bottom of the tank is assumed as rigidly fixed to a rigid ground; and (c) the liquid is assumed to be inviscid, incompressible, and irrotational. The effects of the tank flexibility and soil-structure interaction on the sloshing behavior are not included in the analysis.

Linear and nonlinear sloshing analyses were conducted using a perturbation approach [2].

2.2 Ground Motion Input

For the sloshing response analysis, 75 earthquake records, obtained from 9 different earthquake events with magnitudes ranging from 6.1 to 7.6, were selected as input ground motions. The selected records have epicentral distances ranging from 7.1 to 69.1 km, original PGAs ranging from 0.084 to 1.585 g, and peak A/V ratios from 0.16 to 3.81 g/m/s.

Fig. 1 shows the relations between the peak acceleration and peak velocity of 75 earthquake records for different peak A/V ratios. Twenty-five records have A/V ratios lower than 0.5 g/m/s, twenty-five records are greater than 1.0 g/m/s, and twenty-five records are between 0.5 and 1.0 g/m/s.

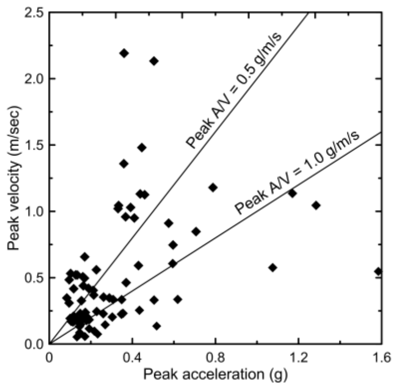
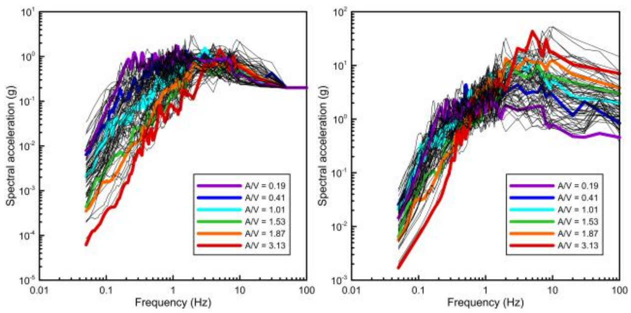


Fig. 1. Peak acceleration vs. peak velocity for different peak A/V ratios

Fig. 2 shows the 0.5% damped acceleration response spectra for all earthquake records normalized to PGA = 0.2 g and PGV = 0.2 m/s. It was revealed that the earthquake ground motions with low A/V ratios are rich in low-frequency contents, while the earthquake ground motions with high A/V ratios are rich in high-frequency content.



(a) Normalized to PGA = 0.2 g (b) Normalized to PGV = 0.2 m/s

Fig. 2. Acceleration response spectra for earthquake records (0.5% damped)

3. Sloshing Responses and Discussions

The sloshing response of rectangular liquid tanks depends on the liquid depth/tank length (d/L) ratio. In a broad tank with a low d/L ratio, most of the fluid participates in the sloshing motion. On the other hand, for a tall tank with a high d/L ratio, only the upper portion of the fluid participates in the sloshing motion. Thus, the sloshing response is significant in a broad tank rather than in a tall tank.

In this study, three types of liquid tanks are considered: a broad tank (d/L = 0.5; 6 m (L) × 3 m (d)), a medium tank (d/L = 1.0; 4 m (L) × 4 m (d)), and a tall tank (d/L = 2.0; 3 m (L) × 6 m (d)).

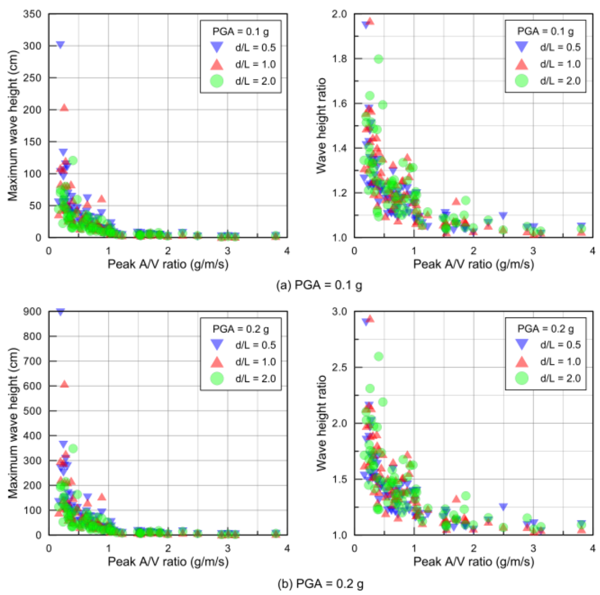


Fig. 3. Maximum wave heights and wave height ratios of tanks for various A/V ratios under different PGAs

Fig. 3 shows the results for a nonlinear analysis and the wave height ratios for various A/V ratios. The wave height ratio is defined as the ratio of maximum wave height from a nonlinear analysis to that from a linear analysis. Regardless of the types of tank, the peak A/V ratios can be classified into three groups according to the sloshing response as A/V ≤ 0.5 g/m/s, 0.5 g/m/s < A/V ≤ 1.0 g/m/s, and A/V > 1.0 g/m/s. Generally, for A/V ≤ 0.5 g/m/s, the wave height response amplifies significantly and has a large variability, whereas for A/V > 1.0 g/m/s, the wave height response is small and nearly constant.

Table I shows the amplification factors of the wave height response for the three A/V range groups. The amplification factors are obtained by dividing the wave heights with the wave heights for A/V > 1.0 g/m/s. For A/V ≤ 0.5 g/m/s, the amplification factors increase with an increase in the PGA level. They are larger in broad and medium tanks than in a tall tank.

Table II shows the wave height ratios for the three A/V range groups. This indicates that the difference between the two results from the linear and nonlinear analyses is significant for A/V ≤ 0.5 g/m/s.

Table I: Amplification Factors of the Wave Height Response

Tank type		PGA (g)	A/V ≤ 0.5	0.5 < A/V ≤ 1.0	A/V > 1.0
Broad	High	0.1	13.4	2.7	1.0
		0.2	17.2	2.9	1.0
	Low	0.1	15.7	4.6	1.0
		0.2	17.9	5.1	1.0
Medium	High	0.1	14.0	4.2	1.0
		0.2	18.9	4.8	1.0
	Low	0.1	18.7	7.7	1.0
		0.2	20.8	8.8	1.0
Tall	High	0.1	8.4	2.5	1.0
		0.2	10.5	2.7	1.0
	Low	0.1	14.8	8.5	1.0
		0.2	14.9	9.4	1.0

Table II: Wave Height Ratios in Different Tanks and PGAs

Tank type	PGA (g)	A/V ≤ 0.5		0.5 < A/V ≤ 1.0		A/V > 1.0	
		Low	High	Low	High	Low	High
Broad	0.1	1.16	1.95	1.09	1.30	1.02	1.20
	0.2	1.31	2.90	1.18	1.59	1.04	1.40
Medium	0.1	1.14	1.97	1.08	1.36	1.02	1.18
	0.2	1.29	2.94	1.16	1.72	1.03	1.36
Tall	0.1	1.09	1.80	1.10	1.34	1.03	1.20
	0.2	1.23	2.60	1.20	1.68	1.05	1.41

4. Conclusions

The sloshing responses of rectangular liquid storage tanks for input ground motions with different peak A/V ratios are investigated.

It is clearly revealed that the peak A/V ratio of earthquake ground motions is a significant parameter in predicting the sloshing response of liquid storage tanks. Regardless of the types of tanks, the peak A/V ratios can be classified into three groups as A/V ≤ 0.5 g/m/s, 0.5 g/m/s < A/V ≤ 1.0 g/m/s, and A/V > 1.0 g/m/s. For the input ground motions with a peak A/V ≤ 0.5 g/m/s, the sloshing response is significant in all types of tanks. In particular, tremendous sloshing responses may occur in the broad tank under a strong ground motion. Therefore, a nonlinear analysis must be used in calculating the sloshing responses. For input ground motions with 0.5 g/m/s < A/V ≤ 1.0 g/m/s, a sloshing response is not significant. However, a nonlinear analysis is recommended because a significant response may occur under a high PGA. For input ground motions with a peak A/V > 1.0 g/m/s, the sloshing response is relatively small in all types of tanks. Thus, a linear analysis may be sufficient for calculating the sloshing responses.

REFERENCES

[1] T.J., Zhu, A.C. Heidebrecht, W.K. Tso, Effect of Peak Ground Acceleration to Velocity Ratio on Ductility Demand of Inelastic Systems, Earthquake Engineering and Structural Dynamics, Vol.16, No.1, pp.63-79, 1988.

[2] Y.S. Choun, C.B. Yun, Nonlinear Analysis of Sloshing in Rectangular Tanks by Perturbation Approach, Journal of the Earthquake Engineering Society of Korea, Vol.6, No.6, pp. 55-64, 2002.