

## Estimation of Sloshing Wave Height in Broad Cylindrical Oil Storage Tanks Using Numerical Methods

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### Abstract

Cylindrical steel tanks are important components of many industrial plants such as oil refineries and chemical plants. Usually failure of cylindrical tanks leads to serious consequences. During the past earthquakes such as 1964 Alaska and 1999 Turkey seismic performance of cylindrical tanks revealed that tanks are seismically vulnerable. Therefore, evaluation of seismic performance of these structures is an important task in seismic prone areas. During an earthquake, a sloshing motion may occur in upper parts of the liquid. In storage tanks during earthquake if fluid wave height in tank increases, the fluid wave may damage the roof or some parts of roof holders. The tanks should resist against unfavourable impacts such as earthquakes. In this paper, 5 tanks with different H/D ratios in an oil refinery complex in Iran were studied using static and dynamical analysis (linear and non-linear). Spectrum and time history linear and non-linear analysis was completed in order to find the fluid wave height and also ratio of wave height to the tank diameter.

**Key word:** Seismic Sloshing Wave, Vulnerability, Cylindrical Tanks, Fluid Wave Height, H/D Ratio

### 1. Introduction

Performance of the liquid storage tanks during the past earthquakes showed that these tanks are seismically vulnerable [1-3]. Earthquake force leads to several failures that can be observed in 7 modes. Sloshing of the liquid in tank during earthquake may damage the roof or some parts of roof holders. Large axial compressive stress in tank shell may lead to elephant-foot buckling (Elasto-Plastic Buckling). Overturning of the tanks is one of the failure modes that occur because of increasing of overturning moment. If the base shear force exceeds the base friction, tank will slide. Uplifting in tanks bottom during earthquake causes breaking the piping system connected to tank. Settlement may affect the tanks in the same way.

During an earthquake, the contained fluid of cylindrical tanks oscillates. The upper parts of the liquid move in a long period motion. This part of liquid is usually known as sloshing or convective liquid.

The lower parts of the fluid have almost a rigid motion similar to the tank shell.

This part is usually known as impulsive liquid. Because of the vertical movement of convective liquid the leakage of fluid or even damage to the tank roof may occur. Hence, the sloshing wave height should be taken into account during the seismic design and/or evaluation of liquid storage tanks. Accordingly, various relations are presented in order to calculate the sloshing wave height. The API relation [4] is one of the most well-known code relations for estimating the sloshing wave height.

In this paper, 5 existing tanks with different H/D ratios located in oil refinery in Iran were studied using static and dynamical analysis (linear and non-linear). Spectrum and time history linear and non-linear analysis is done in order to find the fluid wave height and also ratio of wave height to the tank diameter. All of the selected tanks are unanchored and broad cylindrical steel tanks.

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At first, the tank is simulated in ANSYS program [5] using FEM (Finite Element Method) and the elements are selected in order to be closer to real situation of the tank. SHELL63 element for tank shell, bottom and roof tank modeling and FLUID80 element for liquid had been selected. Also uplifting and unanchored situation has modeled using LINK10 element and GAP.

At the next step, static and dynamic analysis (linear and non-linear) is done. Hydrostatic pressure in tank due to liquid weight has been given using static analysis. To determinate free vibration frequencies of tank (impulsive and convective) modal analysis is done and frequencies of first 1000 modes in three directions has determined and used in spectral analysis to survey maximum wave height due to spectral forces.

Spectral analysis is a linear dynamic one so in order to considering non-linear dynamic analysis, time history analysis due to 3 earthquake records (Tabas, El Centro and Golbaft) has done. Then the liquid level decreases in 4 steps in order to studying tanks with different H/D ratios and for those four new model time history analysis is done again.

**2. Specifications of the Studied Tank**

A tank named TK3001 in an oil refinery complex in Iran was selected to consider static and dynamic analysis and seismic vulnerability survey. Table 1 shows the specification of this tank including diameter, height, shell thickness, shell courses, base anchorage type and roof type.

Table 1.Specifications of The Studied Tank

Tank	H	D	Capacity	Liquid Level	Special Density of Liquid	Base Support	$t_b$	$t_r$	Range of Shell Thickness
	m	m	m <sup>3</sup>	m			mm	mm	
TK3001	14.6	57.97	38500	14	0.9	unanchored	9.5	6.35	8-25

H: heigh  
D: diameter

$t_b$ : thickness of the bottom  
 $t_r$ : thickness of the roof

**3. Analysis**

In order to investigate seismic vulnerability of liquid storage tanks in this paper, linear and non-linear analysis is carried out. Here, a 3D finite element model was prepared using the ANSYS software. For considering the potential uplift of the tank, GAP element was used. The tank wall was modelled using SHELL63 element and the volume by FLUID80 element. According to the hazard analysis , Peak Ground Acceleration (PGA) of 0.4g for

seismic vulnerability with 10% occurrence probability in 50 years with return period of 475 years was considered and according to API650 appendix E the 0.5% damping was used for convective mass and 5% damping for impulsive mass were considered. Site-specific acceleration response spectra of the plant were used in analysis. Also 3compatible earthquake records (such as Tabas , El Centro , Golbaft ) in three directions were considered in time history analysis of the tank in order to study fluid wave height of liquid in the tank during earthquake.

Bottom nodes of tank are allowed to move on vertical direction and fluid elements nodes are allowed to move on tank shell and are allowed to move on vertical direction on the surface of the liquid.

FEM used model of the tank TK3001 in ANSYS software in order to linear and non-linear static and dynamic analysis is shown in Figure 2.

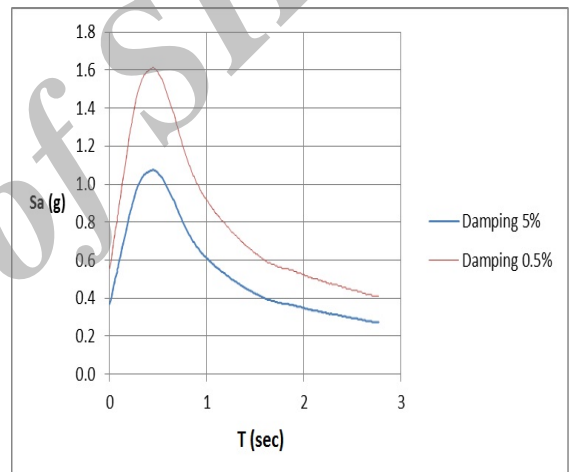


Figure 1. Site-specific response spectra , damping 5% and 0.5% and 10% occurrence probability in 50 years

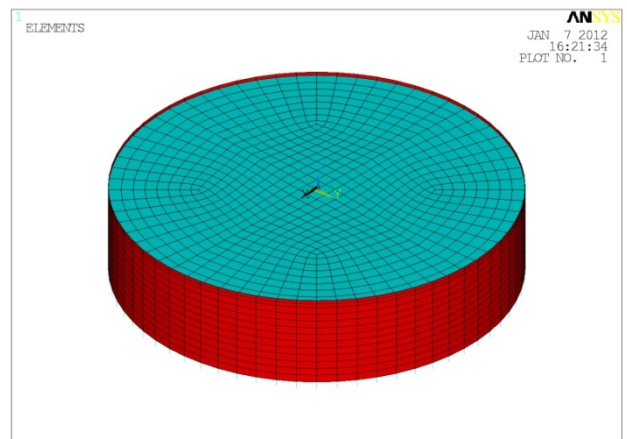


Figure 2. Used FEM model of the tank TK3001 in analysis

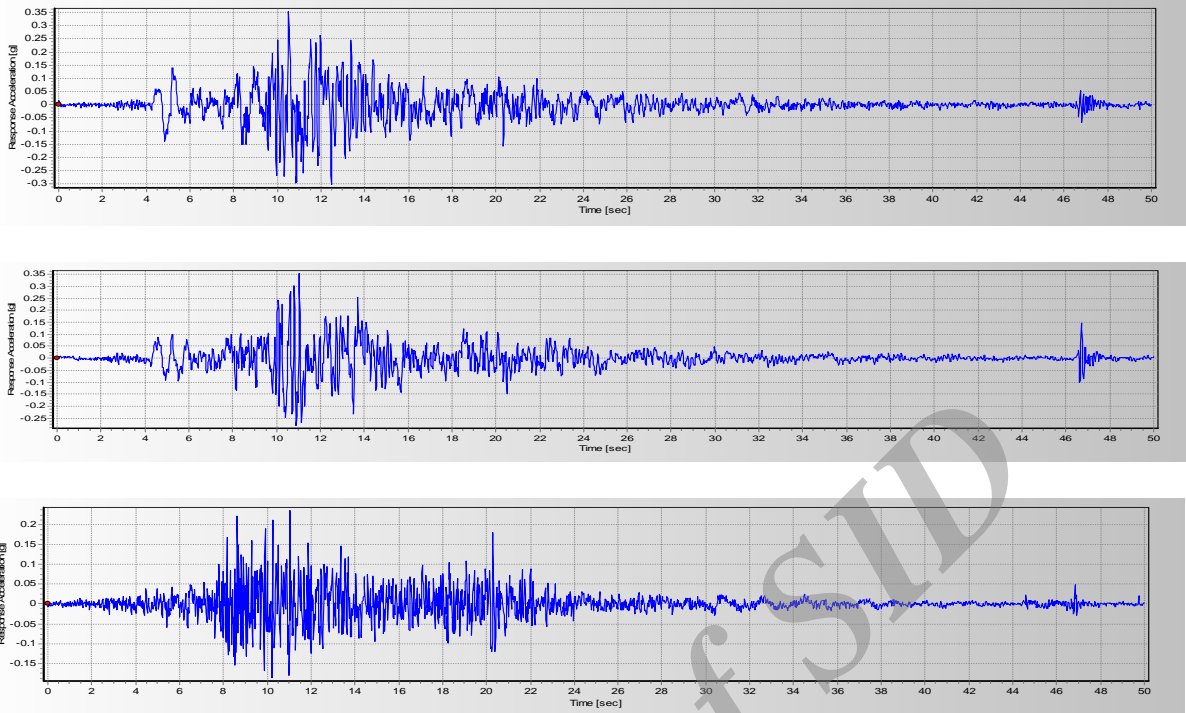


Figure 3. Horizontal(L,T) and Vertical (V) components of Tabas earthquake acceleration record

### 3.1. Results

The hydrostatic pressure on the shell by static analysis was found to be  $1.2\text{kg/cm}^2$ . Results of static analysis verify the modeling method. The first horizontal impulsive and convective modes frequencies of TK3001 tank were found  $3.8\text{ Hz}$  and  $0.1\text{ Hz}$ . Figure 4 shows maximum fluid wave height in tank resulted by spectral analysis. This value is  $1.16\text{ m}$ .

Fluid sloshing displacement of 2 apposite nodes on the upper edge of liquid by Tabas and El Centro records is shown in figures 5 and 6, and the values of maximum fluid wave height is shown in Table 2.

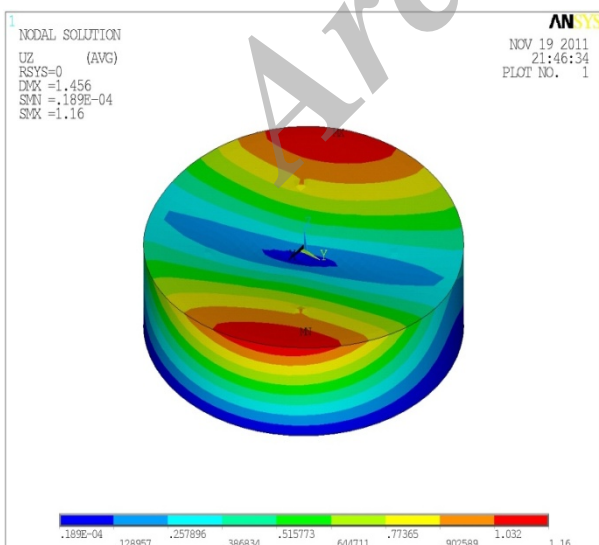


Figure 4. Maximum fluid wave height in tank TK3001 resulted by spectral analysis

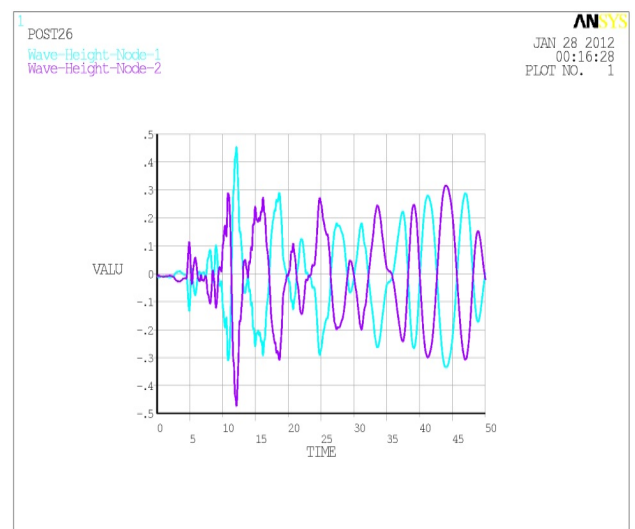


Figure 5. Maximum sloshing wave of liquid affected to Tabas record

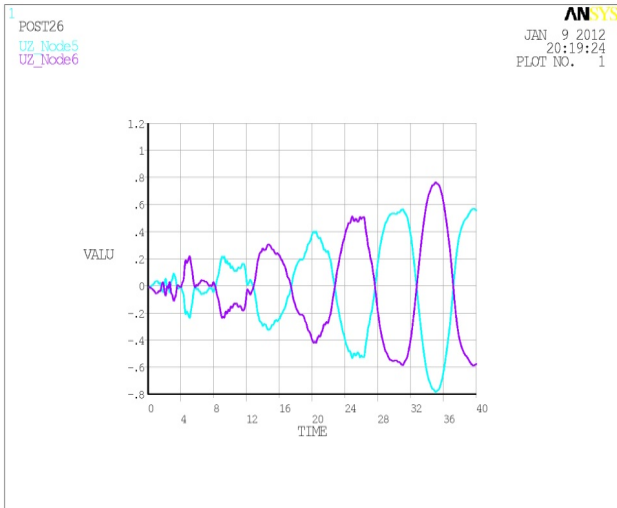


Figure 6. Maximum sloshing wave height due to El Centro time history analysis

Table 2. Sloshing Wave Height Due To 3 Earthquake Records

Record	Maximum Sloshing Wave Height (cm)
Tabas	45.33
El Centro	76.25
Golbaft	10.06

All nodes on the surface of the liquid controlled and observed that in analysis affected Tabas record the maximum fluid sloshing wave occurred in the middle part of liquid surface. In this case, sloshing wave height is 61.22 cm as shown in Figure 7.

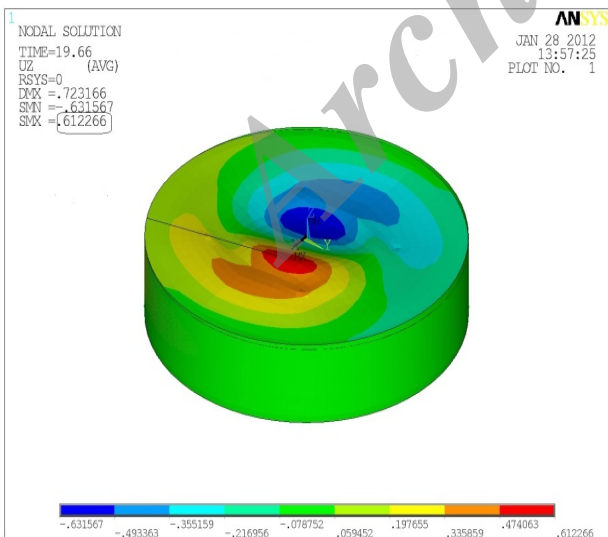


Figure 7. Maximum sloshing wave height in TK3001 tank due to Tabas record

In order to compare the H/D ratio and sloshing wave height in this study, the liquid level in TK3001 tank was decreased in 4 steps and time history analysis using Tabas

record was considered for 4 model. Four models with the same diameter and different height was used. The specifications of the models are shown in Table 3 and the results of time history analysis are shown in the next section.

Table 3. Specification of 5 models of tank TK3001 with different H/D ratio

Model No.	Liquid Level (m)	H/D
1	14	0.24
2	13.4	0.23
3	12.17	0.21
4	10.95	0.19
5	9.74	0.17

Sloshing wave height values of liquid in tank TK3001 due to time history analysis by Tabas earthquake record and API650 values is shown in Table 4 and Figure 7.

Table 4. Sloshing wave height (Analytical and API650 values) of 5 models due time history analysis

Model No.	Liquid Level (m)	H/D	Sloshing Wave Height (Analytical) (cm)	Sloshing Wave Height (API650) (cm)
1	14	0.24	61.22	65.69
2	13.4	0.23	59.48	63.90
3	12.17	0.21	57.88	59.93
4	10.95	0.19	56.24	55.57
5	9.74	0.17	49.72	50.83

Figure 8 indicates the linear interpolation of results of numerical analysis. Comparison of sloshing wave height between analytical values and API 650 values for 5 models due to time history analysis is shown in Figure 9.

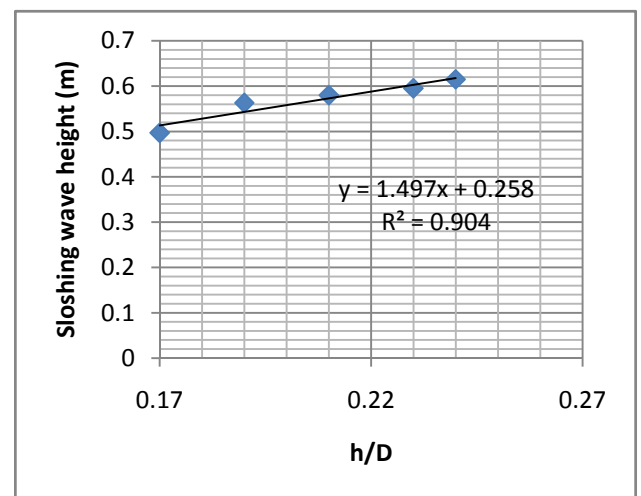


Figure 8. Diagram of sloshing wave height with respect to H/D ratio (Analytical and API650 values)

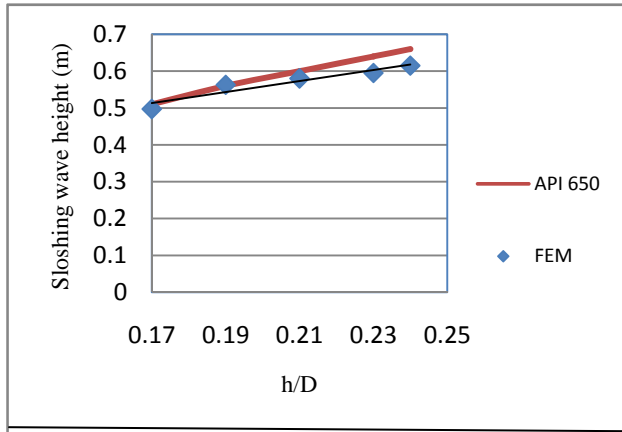


Figure 9. Linear respect of sloshing wave height to H/D ratio

#### 4. Conclusion

This paper focused on estimation of sloshing wave height of the liquid in cylindrical tanks due to earthquakes. Here, broad tanks with different levels of contained liquid were modelled and numerically analysed. The focus of this study is broad tanks. The results of numerical analyses were compared to those estimated by code relations. Results showed that in extremely broad tanks the sloshing wave height estimated by these two methods are very close to each other. By increasing the height to diameter of the contained liquid, the difference of analytical and numerical results increases. In other words, results of this study indicate that provisions of API650 are conservative for evaluation of sloshing motion of liquid in tall cylindrical tanks. Furthermore, the results of spectral analysis were remarkably higher than those obtained by time history analyses and code relations.

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