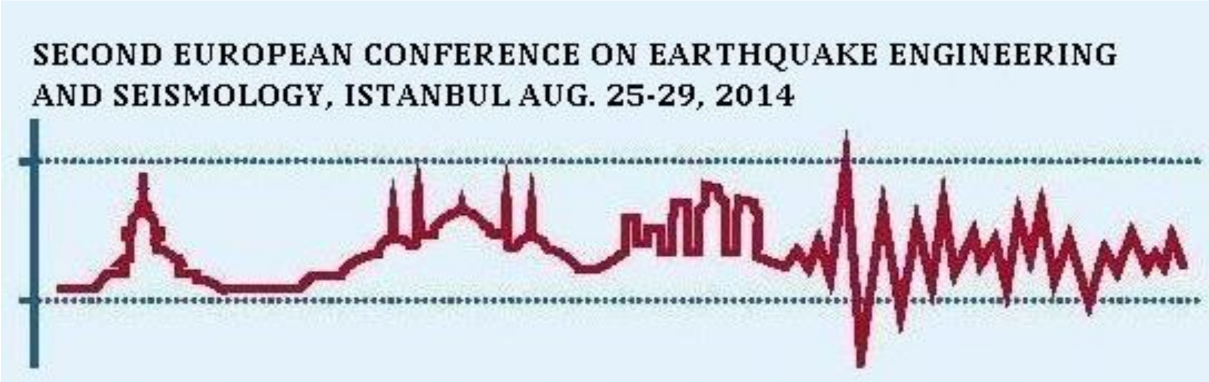

SIESMIC SLOSHING IN CYLINDRICAL TANKS WITH FLEXIBLE BAFFLES

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ABSTRACT

Sloshing has been one of the major concerns for engineers in the design of liquid cylindrical tanks. During many past major earthquakes; failure of cylindrical liquid storage tanks due to sloshing has been led to fire, explosions, disrupt production, serious environmental hazards and large amounts of financial loss. On the other hand, destructive effects of sloshing phenomenon can be suppressed in a passive manner by introducing additional sub-structures called baffles into tanks. The main purpose of constructing these sub-structures is to alter period of sloshing action beneficially and to increase hydrodynamic damping ratio.

There are numerous experimental and numerical studies in the literature, where the effect of geometric parameters of baffles, such as configurations, widths, thicknesses, and locations, on hydrodynamic damping ratio and sloshing frequency has been investigated. However, the influence of the flexibility of baffles on the hydrodynamic damping ratio in large tanks has not been numerically evaluated so far. Therefore, the main aim of this paper is to numerically quantify the effect of baffle flexibility on the sloshing response of cylindrical liquid storage tanks. LS-DYNA program is chosen as a numerical analysis tool to perform coupled fluid-structure interaction analysis of tanks. The finite element models of tanks are validated using existing experimental studies in the literature. A parametric study is carried out on cylindrical tanks by changing geometric parameters of flexible baffles. Hydrodynamic damping ratio of sloshing is evaluated under different earthquake motions.

INTRODUCTION

Sloshing response of baffled tanks can be investigated using analytical, experimental or numerical methods. The derivation of an analytical solution for the sloshing response of a liquid in a baffled tank includes many assumptions and simplifications on the tank material, fluid properties and input motion. The resulting closed form solutions might lead to different behaviour than the response of the actual systems. Even though, experimental works are necessary to study the actual behaviour of the system, they are time consuming, very costly and performed only for specific boundary and excitation conditions. However, an appropriate numerical method with fluid-structure interaction techniques can efficiently predict the sloshing response of a baffled tank.

The effects of baffle flexibility on sloshing was investigated in the study of Stephens (1967) by performing a series of experimental tests to determine the effectiveness of lightweight, flexible baffles for damping liquid oscillations in relatively large cylindrical tanks.

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The main objective of this paper is the numerical assessment of the response of baffled tanks under external excitations taking into account the flexibility of the baffle.

A fully nonlinear fluid-structure interaction (FSI) algorithm of the finite element method (FEM) is employed to evaluate the response of baffled tanks by using the analysis capabilities of general purpose finite element code LS-DYNA. The ALE method is used to transfer the interaction effects between the fluid and the structure. The numerical model is first verified using an existing numerical study in the literature. Following the verification of the numerical model, the hydrodynamic damping ratio of sloshing in a 3D rigid tank is assessed for different baffle flexibility.

Finally, a parametric study is carried out on relatively large cylindrical tanks. The most efficient baffle flexibility for 3D rigid cylindrical tanks is investigated in terms of seismic sloshing wave height.

VERIFICATION OF THE NUMERICAL MODEL

In this section, numerical study is carried out on 3D cylindrical baffled tanks under harmonic motions, and the time history of the free surface wave sloshing height at a specific location obtained by ALE method is compared with the results of the reference solution performed by Maleki and Ziyceifer (2008). The effects of baffle parameters such as, position, dimension and shape on the non-linear response of liquid in the tanks were examined. A 3D rigid cylindrical tank with a radius (r) of 100 cm is filled with water up to a height (H) of 50 cm. The baffle is assumed to be rigid and it has a length (r_b) of 7.5 cm. It is placed at a depth (h) of 30 cm from the bottom of the tank (Figure 1). The tank was subjected to corresponding sloshing frequency with displacement amplitude of 1.5 mm (Figure 2). This tank numerical model was generated by LS-DYNA (Figure 3) and considered as a reference solution for the verification of the numerical model employed in this paper.

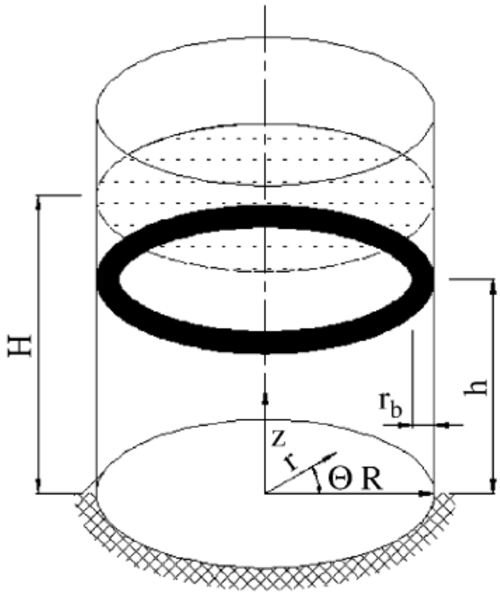

Figure 1. 3D cylindrical baffled tank parameters for verification analysis

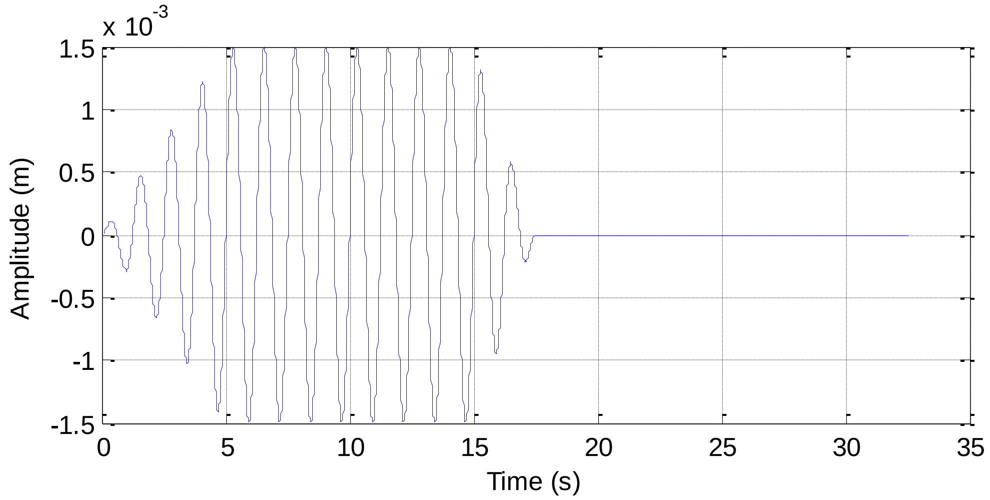

Figure 2. Harmonic motion record for verification analysis

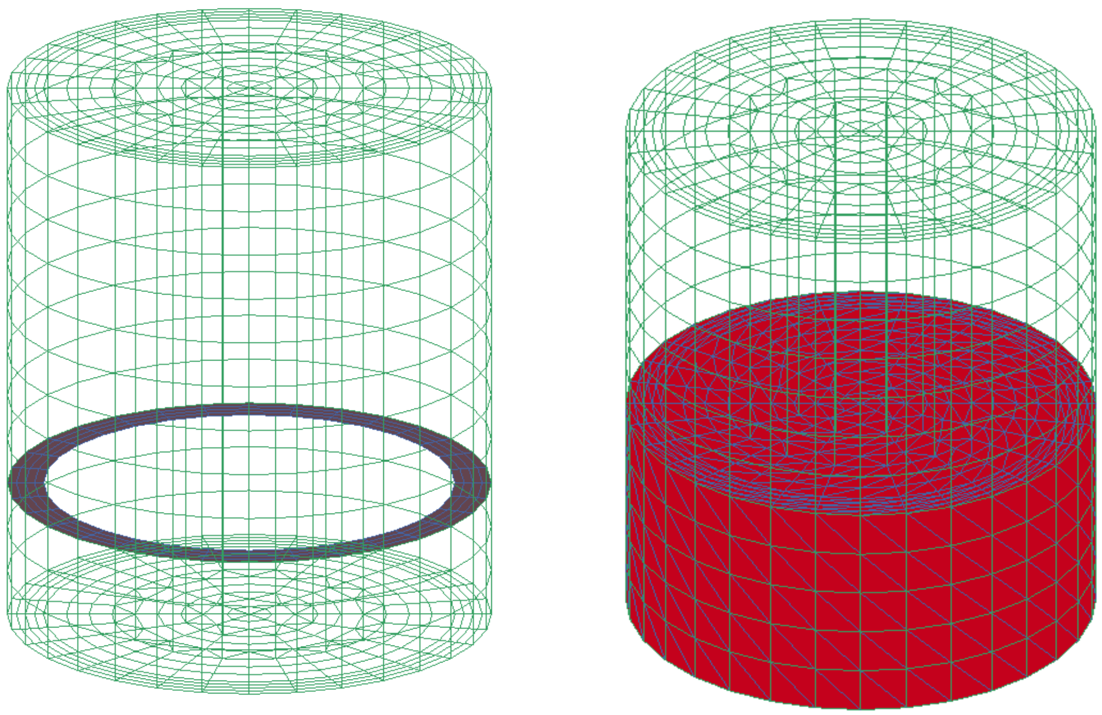

Figure 3. 3D numerical model for cylindrical tank, baffle, and fluid for verification analysis

The hydrodynamic sloshing damping ratio ξ can be determined experimentally in time domain from the free vibration response of sloshing using the logarithmic decrement method. In this method, tank is forced using a harmonic motion with a frequency equal to its corresponding fundamental sloshing frequency until reaching a steady state or enough large free surface displacement. Then, the oscillation is quickly stopped and the decay rate of the free surface displacement is recorded. Logarithmic decrement, which is the natural logarithmic value of the ratio of peak values of displacement, can be used to obtain sloshing damping ratio ξ ;

$$\frac{2\pi\xi}{\sqrt{1-\xi^2}} = \frac{1}{n}\ln\left(\frac{D_i}{D_{i+n}}\right) \tag{1}$$

where, D_i and D_{i+n} are the sloshing amplitudes measured in i and i +n oscillation cycles (Ibrahim,1999)

In the current study, the logarithmic decrement method is employed to compute sloshing damping in the 3D rigid baffled tanks and results compared with the results of theoretical and experimental works of Maleki and Ziyceifer (2008). The sloshing wave time histories for 3D rigid tank model obtained using the ALE method is shown in Figure 4. In addition, a damping curve is also superimposed in this figure.

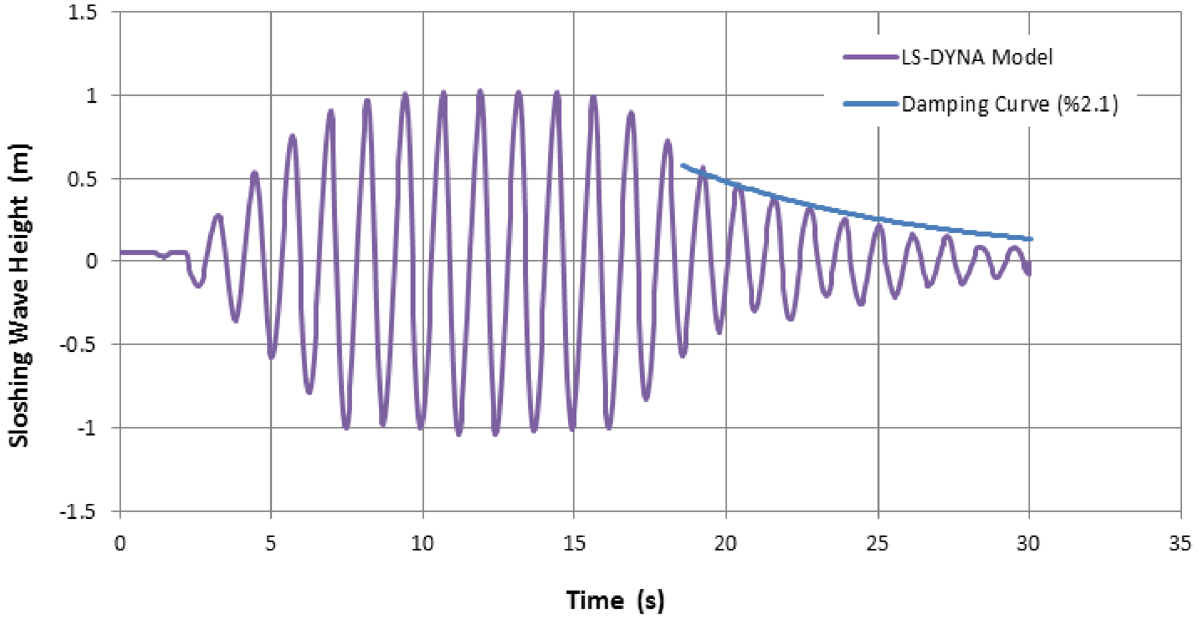

Figure 4. Sloshing wave height time history for the 3D tank model with the damping curve of %2.1

The hydrodynamic sloshing damping ratio obtained using the ALE method is compared with the theoretical and experimental damping ratios. (Table 1)

Table 1.Comparison of damping ratios

ζ EXPERIMENTAL	ζ MALEKI-ANALITICAL	ζ LS-DYNA
0.016	0.022	0.021

NUMERICAL 3D CYLINDRICAL TANK MODEL WITH FLEXIBLE BAFFLE

The effectiveness of baffles on the sloshing damping ratio in a rigid tank under harmonic motion is evaluated numerically. In this section, real earthquake motions are used to assess the sloshing response of flexible baffled tanks. 3D cylindrical rigid tank model, which is illustrated in Figure 5, is used in the numerical simulations. A tank with a radius (r) of 40.0 m is filled up to a height (W) of 10 m with water, which has a density 1000 kg/m^3, a bulk modulus of 2.2 10^9 Pa, and dynamic viscosity of 10^{-3} Pa.sec. The baffle has a length (b) of 2.0 m and is placed at a depth (h) of 9.0 m from the bottom of the tank.

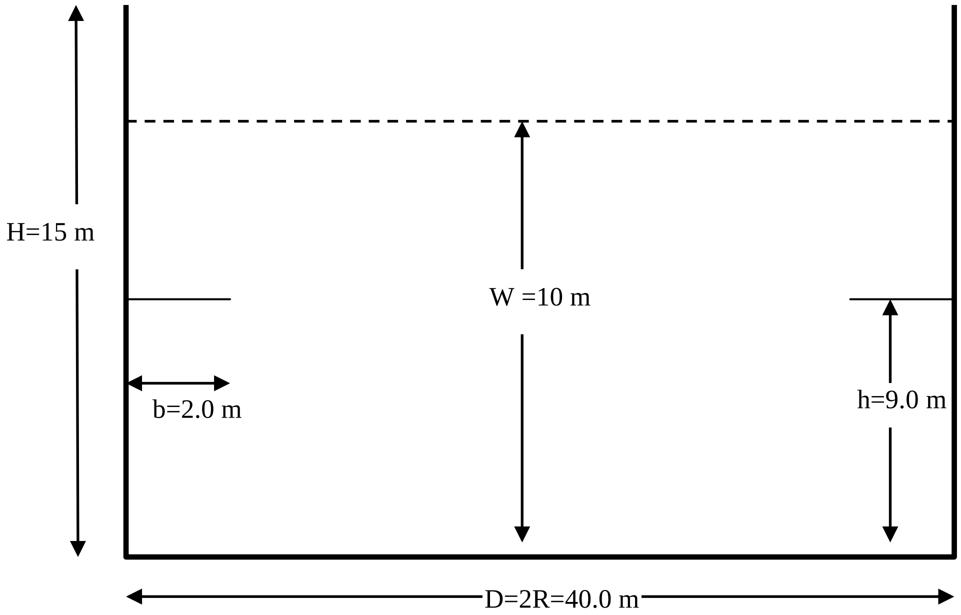

Figure 5. 3D cylindrical baffled tank geometry

The effect of baffle flexibility on the sloshing response of cylindrical liquid storage tanks is quantified numerically. In the numerical analyses six different baffle thicknesses are used: t= 0.0005, 0.001, 0.002, 0.004, 0.006 and 0.008 where b is the baffle width. The baffle element has elastic material model, which has a density 7800 kg/m^3, a elastic modulus of 2.0 10^{11} Pa

Three earthquake records for time history analysis of the baffled tanks structures are selected from Pacific Earthquake Engineering Research (PEER) Center, NGA strong motion data base and listed in Table 2. The selected earthquake accelerograms are illustrated in Figure 6 to Figure 8.

In the analysis, the response of un-baffled tanks under these earthquake motions is assessed. It is observed that maximum sloshing wave height under these original records was very low. Therefore, these records are scaled with certain factors to obtain a maximum sloshing wave height which can reach the value of freeboard distance. It should be noted that the wave height generated by the scaled motion is not allowed to exceed the freeboard distance in order to prevent impacts of sloshing waves on the tanks roof surface.

Table 2. Earthquake records for the time history analysis of 3D baffled tanks

Analy. Name	Earthquake	Moment Magnitude	Station	Component	Epicentral Distance (km)	Soil type (NEHRP)	Scale Factor
EQ1	Landers 06.28.1992	7.28	Yermo Fire	LANDERS\YER360.AT2	85.99	D	1.24
EQ2	Kocaeli 08.17.1999	7.51	Yarimca	KOCAELI\YPT060.AT2	19.30	D	1.17
EQ3	Cape Mendocino 04.25.1992	7.01	Fortuna	CAPEMEND\FOR090.AT2	29.55	C	2.29

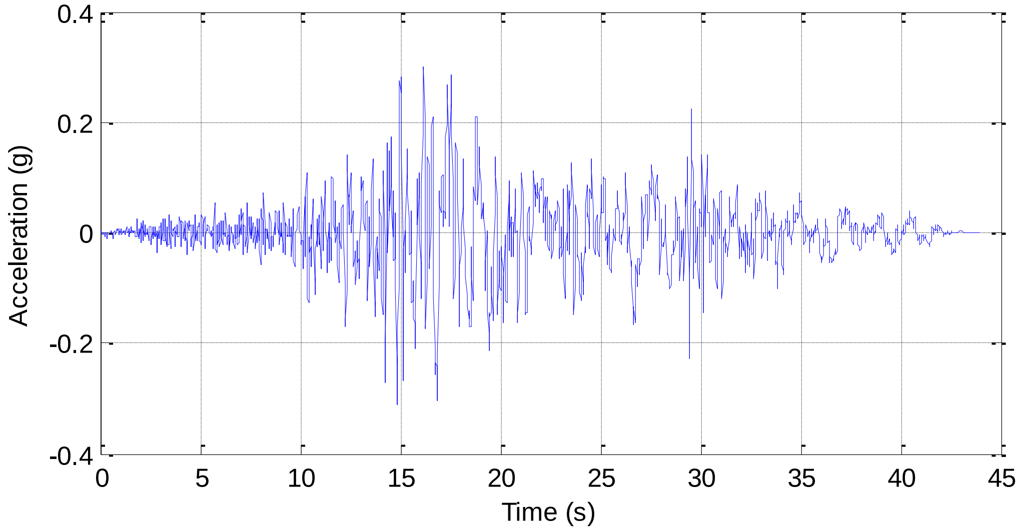

Figure 6. EQ1 record for the time history analysis of 3D baffled tanks

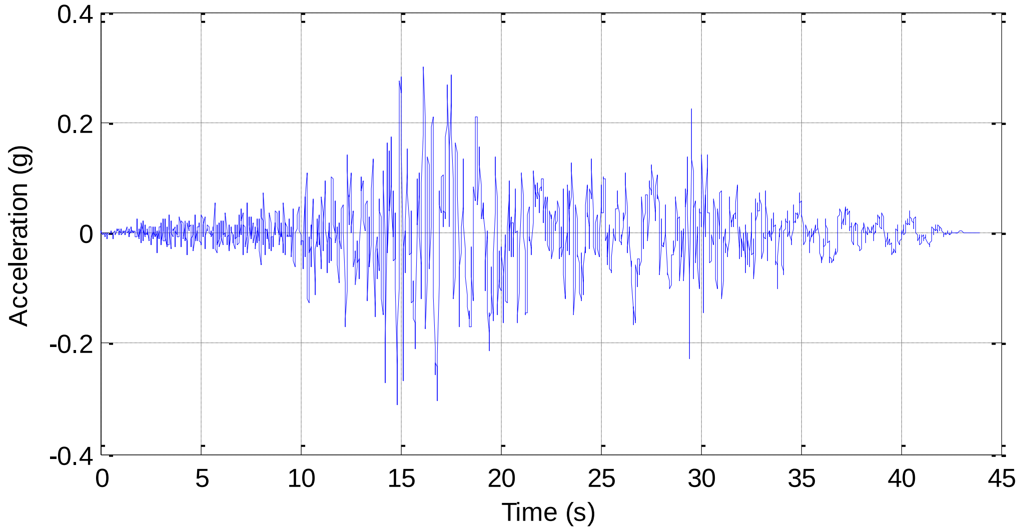

Figure 7. EQ2 record for the time history analysis of 3D baffled tanks

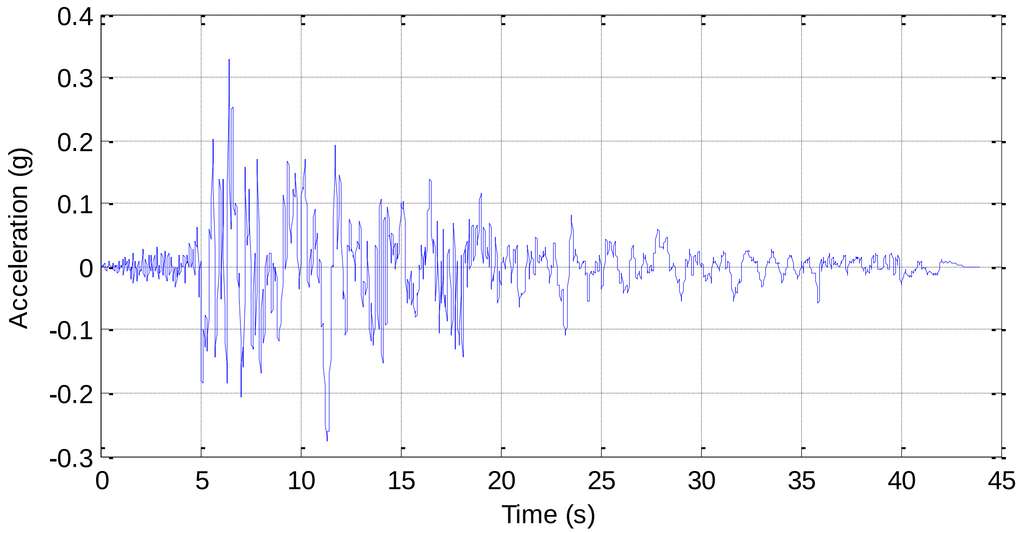

Figure 8. EQ3 record for the time history analysis of 3D baffled tanks

SEISMIC RESPONSE OF 3D CYLINDRICAL TANK MODEL WITH FLEXIBLE BAFFLE

The maximum sloshing wave height for each baffle flexibility is compared with the maximum wave height for rigid baffled tanks and un-baffled tanks. The flexible baffles deformation for least thickness under EQ1 excitation, corresponding the maximum sloshing time, is illustrated Figure 9. Where baffle thickness, t, is considered to be 0.001.

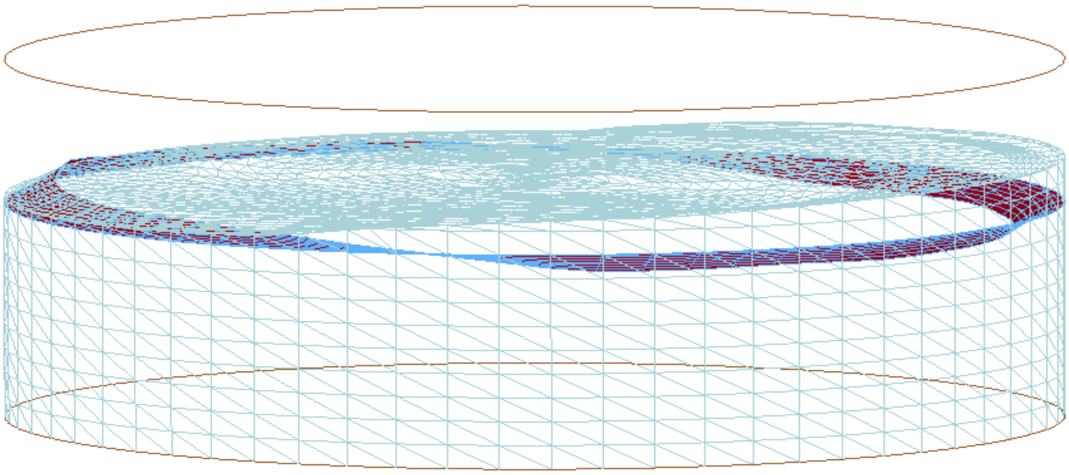

Figure 9. Flexible baffled deformation corresponding the maximum sloshing

The efficiency of baffles flexibilities on supressing the sloshing response of tanks can be better quantified by comparing the maximum wave height in flexible baffled tanks with that in un-baffle tanks and rigid baffled tanks. The maximum sloshing wave height for tank models under different earthquake excitation are given in Figure 10 to Figure 12, respectively. The average values of the maximum sloshing wave height due to three different earthquakes are obtained for each baffle thickness (t) combinations. Figure 13 shows the average maximum sloshing height for all baffle flexibilities. As can be observed from Figure 13 for some certain baffle thicknesses (t is between 0.004 and 0.008) average wave height is not effective than unbaffled or rigid baffled tanks. The most efficient baffle thickness is 0.0005. The results of the maximum sloshing wave height for tank models under different earthquake excitations demonstrate that the flexibility of the baffle, in average, reduce the sloshing wave height significantly.

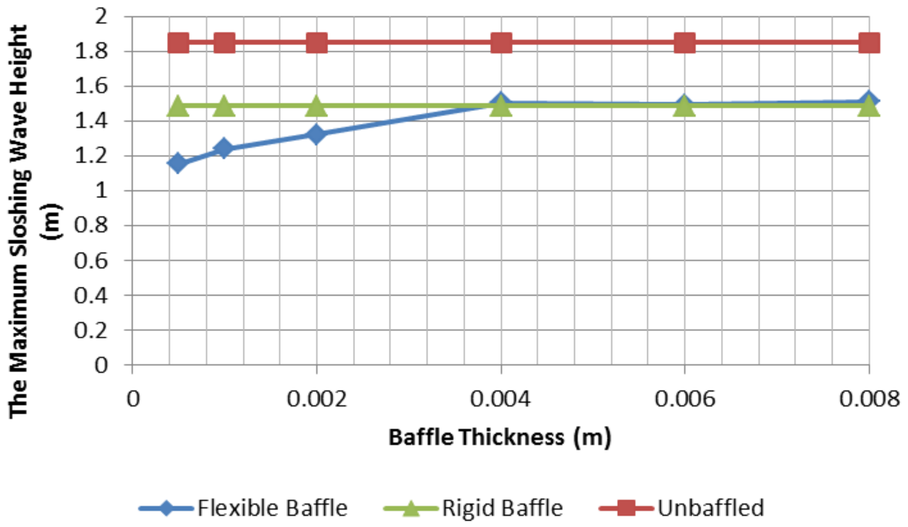

Figure 10. The maximum sloshing wave for flexible baffled, rigid baffled and un-baffled tanks under EQ1 excitation

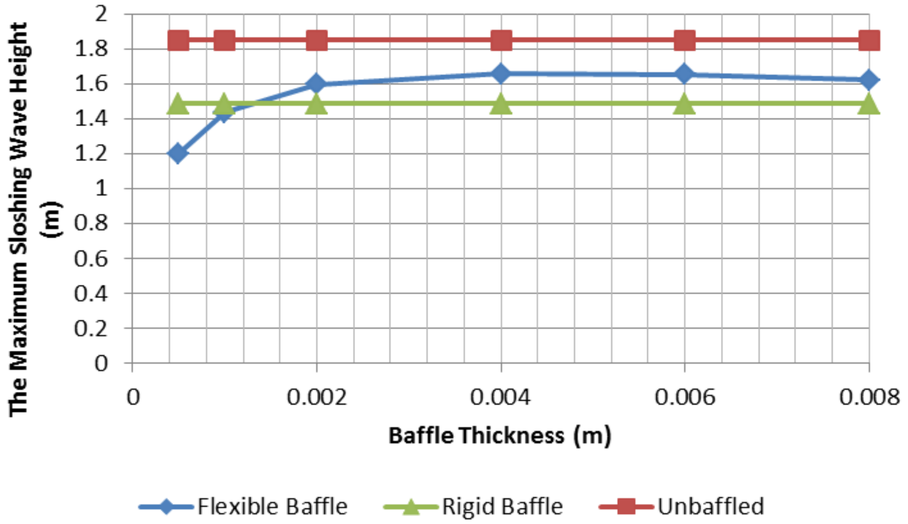

Figure 11. The maximum sloshing wave for flexible baffled, rigid baffled and un-baffled tanks under EQ2 excitation

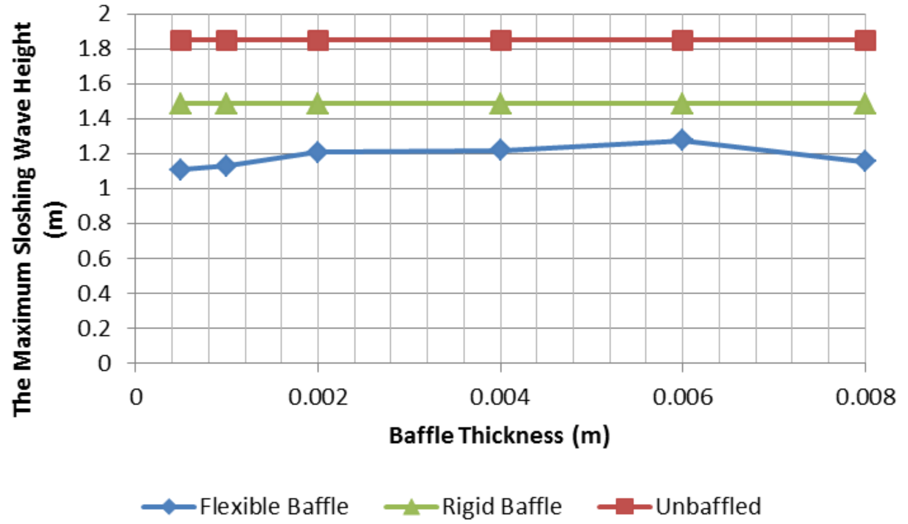

Figure 12. The maximum sloshing wave for flexible baffled, rigid baffled and un-baffled tanks under EQ3 excitation

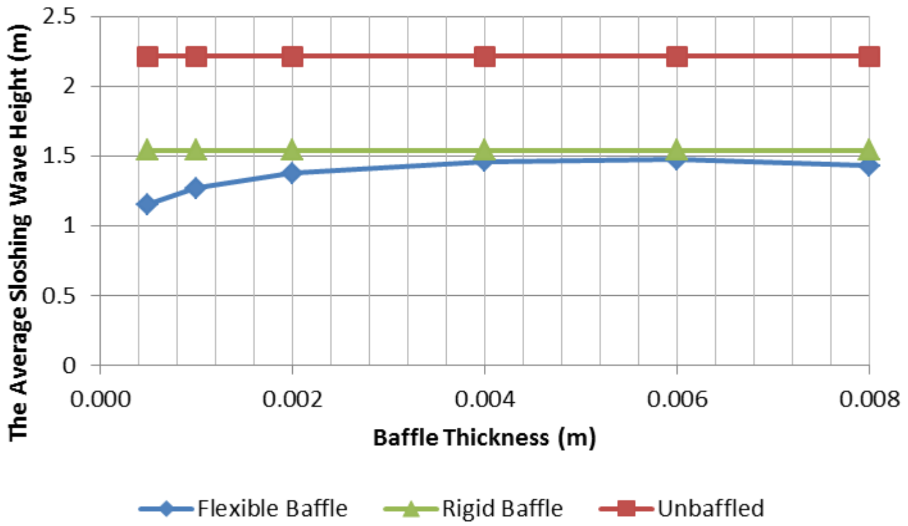

Figure 13. The average maximum wave heights for flexible baffled, rigid baffled and un-baffled tanks

CONCLUSIONS

The effects of baffle flexibility on sloshing height of cylindrical tanks under earthquake ground excitations is studied numerically utilizing fully nonlinear fluid-structure interaction (ALE) algorithm of the finite element method (FEM). The numerical results of 3D model cylindrical tanks demonstrate that the flexibility of the flexible baffle increase the effectiveness of the baffle for reduction of the sloshing waves. The comparison of the analyses results of different baffle thicknesses subjected for three earthquake records with the rigid baffle shows the variations of the sloshing suppression effects due to the flexibility of the baffle. In average, the flexibility of the baffle may reduce the sloshing wave height of the fluid in the tank by the ratio %25 compared to rigid baffle and %55 compared to un-baffled tank.

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