Seismic Response of Baffled Liquid Containment Tanks

Zuhal Ozdemir[1], Yasin Fahjan[2] and Mhamed Souli[3]

[1]Department of Civil and Structural Engineering, University of Sheffield, UK

[2]Department of Earthquake and Structural Engineering, Gebze Institute of Technology, Turkey

[3]Laboratoire de Mécanique de Lille, Université des Sciences et des Technologies de Lille, France

Abstract

The failure of liquid storage tanks due to earthquake induced sloshing action of the liquid was extensively observed during many past major earthquakes. The destructive effects of sloshing can however be suppressed in a passive manner by introducing additional sub-structures such as baffles into tanks. The main aim of constructing these sub-structures is to alter the period of sloshing action beneficially and to increase hydrodynamic damping ratio.

The main aim of this paper is to numerically quantify the effect of baffles on the response of 2D rigid tanks. In this paper, LS-DYNA program is chosen as a numerical analysis tool due to its high degree of flexibility. The numerical model is first verified using an existing numerical study in the literature and a strong correlation between reference solution and numerical results is obtained in terms of sloshing wave height. Following the verification of the numerical model, the hydrodynamic damping ratio of sloshing in a 2D rigid baffled tank is assessed for different baffle positions. Finally, a parametric study is carried out on 2D rigid tall and broad baffled tanks in order to assess the effect of baffle on the sloshing wave height under different earthquake motions.

1 Introduction

One of the most severe effects of sloshing action on liquid containment tanks was observed in the Tüpraş oil refinery during the 1999 Kocaeli earthquake. Insufficient freeboard and large amplitude sloshing action observed in fixed-roof tanks resulted in plate buckling at the roof level and excessive joint stresses and rupture at the roof-shell junction. Floating roofs of several tanks sank into contained liquid due to sloshing. However, the destructive effects of sloshing phenomenon can be suppressed in a passive manner by introducing additional sub-structures called baffles into tanks.

Baffles can be introduced in tanks in a variety of different configurations. These structures affect sloshing response in tanks in two ways: 1-) Baffles change the fluid natural frequencies depending on the shape, size, and position of baffles. 2-) Anti-slosh baffles are expected to increase hydrodynamic damping of sloshing under prescribed filling conditions, tank orientation, and external excitation. However, optimum design of these structures is essential in order to achieve maximum performance and to avoid amplification of the response.

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. Consequently, 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 behavior of the system, they are very 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 fluid-structure interaction and sloshing response of rigid and flexible tanks have attracted attention of many researchers over the last few decades. However, a recent paper of Rebouillat and Liksonov [1] which reviews the publications devoted to the numerical modelling of the fluid-structure interaction and sloshing phenomenon in partially filled liquid containers reveals that the number of studies carried out on baffled tanks is significantly less than that undertaken on un-baffled tanks. Moreover, the numerical studies carried out on baffled tanks are still limited to cubic or rectangular tank shapes with elastic baffles [2]. Despite the fact that considerable progress has been made in modelling the sloshing phenomenon, the assessment of sloshing effects in baffled tanks is still of interest for potential developments.

This paper, therefore, focuses on the assessment of the response of baffled tanks under external excitations in order to fill the gap in the literature concerning the assessment of sloshing effects in such structures. 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 2D rigid baffled tank is assessed for different baffle positions. Finally, a parametric study is carried out on 2D rigid tall and broad baffled tanks. Since the shape and design concept of the sloshing damper varies depending on the type of external excitation and the container shape, the most efficient baffle position for 2D rigid baffled tanks is investigated in terms of seismic sloshing wave height.

2 Verification of the numerical model

In this section, an existing numerical study, which was carried out on 2D rigid baffled tanks under harmonic motions, is considered as a reference solution for the verification of the numerical model employed in this paper. The time history of the free surface wave height at a specific location obtained by ALE method is compared with the results of the reference solution performed by Biswal et al. [3]. The effects of baffle parameters such as, position, dimension and number on the non-linear response of liquid in the tanks were examined in this reference study.

A 2D rigid rectangular tank with a width of 1.0 m is filled with water (ρ= 1000 kg/m^3) up to a height of 0.5 m (Fig. 1). The baffle is assumed to be rigid and it has a length of 0.40 m. It is placed at a depth of 0.10 m from the bottom of the tank and on the left boundary of the tank. The tank is subjected to sinusoidal horizontal acceleration, $\ddot{x} = -\,\omega^2\, x_0\, Sin\ \omega t$, where $x_0 = 0.002\ m$ and $\omega = 5.29\ rad/s$. Fig. 2 presents the time history response of the free surface elevation at the right wall of the tank obtained by the reference solution and the ALE method. The findings of two methods are in general highly consistent in terms of peak level timing, shape and amplitude of sloshing wave. The ALE method predicts slightly higher positive sloshing wave height for the first 7 seconds, while the reference solution provides higher wave amplitude for the rest of the analysis. On the other hand, the negative wave height obtained using the reference solution is higher than that of observed by the ALE method. As can be seen from the solutions of two methods, the positive (upward) sloshing wave amplitudes are always higher than the negative (downward) ones. This phenomenon is a classical indication of a nonlinear behaviour of sloshing and caused by suppression effect of the tank base on the waves with negative amplitude.

3 Hydrodynamic damping due to baffles

In baffled tanks, the flow separation around baffles causes an increase in energy dissipation and, in turn, hydrodynamic forces which act on the tank may decrease. Isaacson and Premasiri [4] proposed a theoretical model to calculate hydrodynamic forces of baffled tanks. In this model, energy dissipation associated with baffles is predicted from drag forces acting on such structures and the corresponding damping effects on the hydrodynamic forces are taken into account by modifying the free surface boundary condition used in the potential flow theory. In order to verify theoretical model, Isaacson and Premasiri [4] performed a series of shaking-table test on baffled tanks which are 0.5 m long, 0.5 m wide and 0.5 m high. In these tests, the tank is filled with water (ρ = 1000 kg/m^3) up to a height of 0.25

m (Fig. 3). The horizontal baffles, which have a length of 0.04 m, were oriented perpendicular to the tank side walls. Three different baffle elevations, h, are considered as shown in Tab. 1.

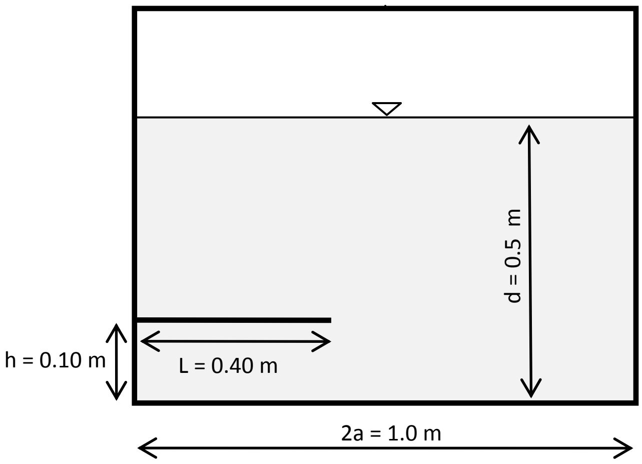


Fig. 1: 2D rectangular tank with a horizontal baffle [3].

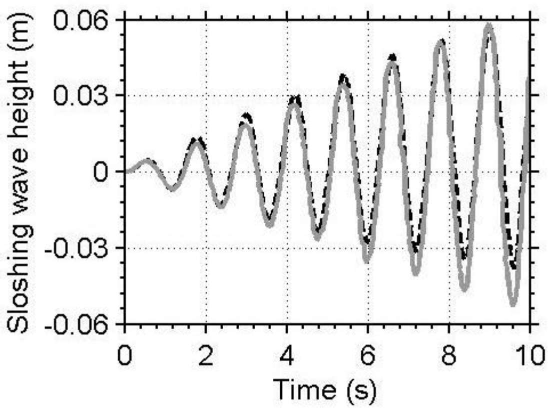


Fig. 2: The sloshing wave height at right wall of the 2D rectangular rigid tank with a horizontal baffle under sinusoidal base motion. The results obtained using the ALE method (black dotted line) are compared with those obtained by Biswal et al.[3] (grey line).

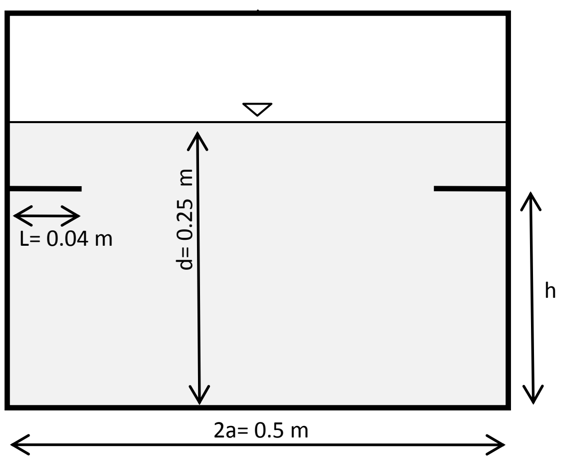


Fig. 3: 2D rectangular tank with multiple baffles [4]

Tab. 1: Tank dimensions [4]

Test	h/d	h (m)
Tank A	0.6	0.15
Tank B	0.7	0.175
Tank C	0.8	0.20

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 [5]:

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

where, D_i and D_{i+n} are the sloshing amplitudes measured in i and i +n oscillation cycles.

In the current study, the logarithmic decrement method is employed to compute sloshing damping in the 2D rigid baffled tanks and results compared with the results of theoretical and experimental works of Isaacson and Premasiri [4]. In the numerical model, element size is considered as 0.025 m for the ALE fluid elements and the tank mesh. The amplitude of the sinusoidal harmonic motion is considered as 0.01 m. The circular frequencies ω_n of the harmonic motion are obtained using sloshing frequencies:

$$\omega_n^2 = g\frac{(2n+1)}{2a}\tanh\left(\frac{(2n+1)\,\pi}{2a}d\right) \tag{2}$$

where g is gravitational acceleration and n represents mode number.

The sloshing wave height time histories for different baffle positions obtained using the ALE method are shown in Figures 4, 5 and 6. In addition, damping curves are also superimposed in these figures. The sloshing damping ratio using the logarithmic decrement method can be obtained in many different ways. Any two consecutive oscillation cycles which occur following the end of motion can be used in Equation (1). As an alternative, the amplitude of non-sequential peaks can also be used in Equation 1 in order to calculate the damping ratio. Therefore, these various different alternatives can give a variety of sloshing damping ratios. In this work, a mean damping ratio is obtained by taking an average from a number of damping ratios of different sequential peaks and this average damping value is represented by a damping curve (grey line) in Figures 4, 5 and 6. Each of these damping curves represents an average damping ratio for each sloshing wave height time history.

In Tab. 2, the hydrodynamic sloshing damping ratios obtained using the ALE method is compared with the theoretical and experimental damping ratios predicted by Isacson and Premasiri [4]. As can be seen from this table, although theoretical model deviates from the experimental findings, the ALE method can predict experimental damping ratios with high accuracy. Seismic tank design codes [6, 7] specify a damping ratio of 0.5 % for the sloshing action of the contained liquid. Tab. 1 also shows that the sloshing damping ratio of baffled tanks is around 1- 2%. Therefore, baffles are effective at increasing slohing damping. However, an extensive study is necessary to assess the effect of position and size of baffles on the seismic response of tanks. Therefore, next section is devoted to a parametric study of sloshing response of baffled tanks under earthquake motions.

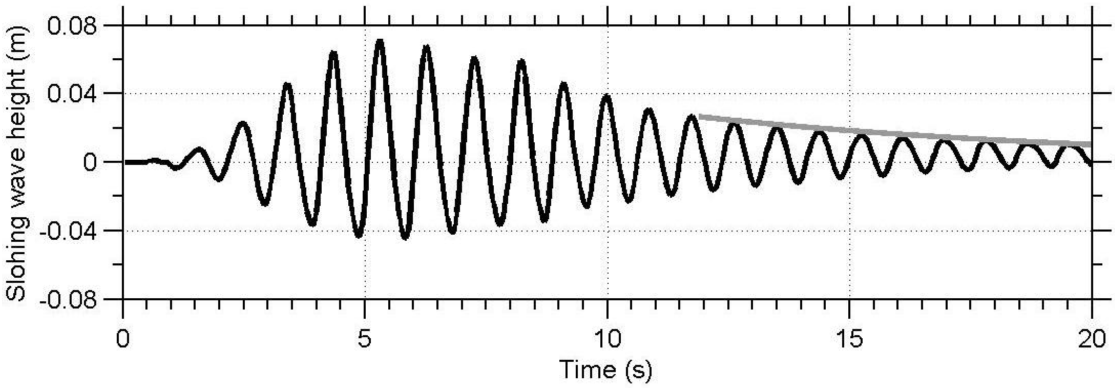


Fig. 4: Sloshing wave height time history (black line) for the Tank A along with the damping curve of 1.5 % (grey line)

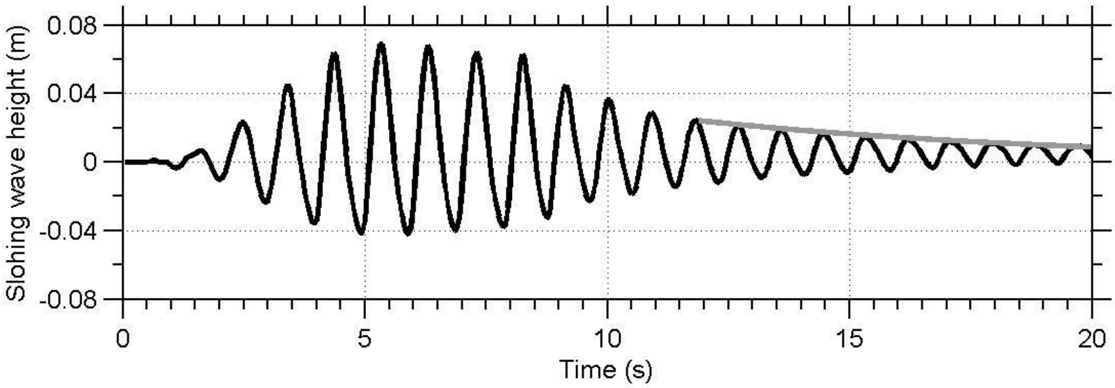


Fig. 5: Sloshing wave height time history (black line) for the Tank B along with the damping curve of 2.0 % (grey line)

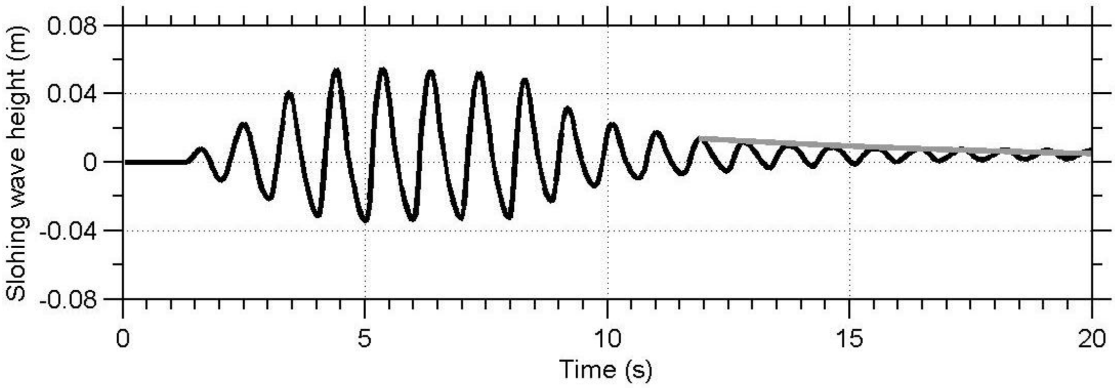


Fig. 6: Sloshing wave height time history (black line) for the Tank C along with the damping curve of 2.4 % (grey line)

Tab. 2: Comparison of damping ratios

Test	Experimental (Isacson and Premasiri, 2001) ζ	Theoretical (Isacson and Premasiri, 2001) ζ	ALE method ζ
Tank A	0.013	0.018	0.015
Tank B	0.018	0.031	0.020
Tank C	0.025	0.050	0.024

4 Seismic response of 2D rigid baffled tanks

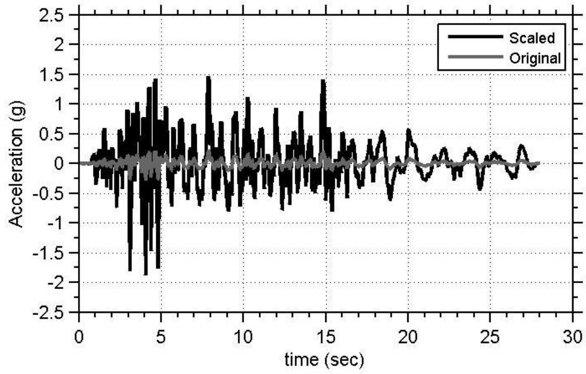
In the previous section, the effectiveness of baffles on the sloshing damping ratio in a 2D rigid tank under harmonic motion was evaluated numerically. In this section, real earthquake motions are used to assess the sloshing response of baffled tanks. Two different type of tanks, which are one tall and one broad tanks, are used in the numerical simulations. The tall tank (Tank I) is considered to have a width of 10.0 m and a total height of 15 m while the broad tank (Tank II) has a width of 40 m and a total height of 15 m. For both cases, the tanks are filled up to a height of 10 m with water, which has a density of 1000 kg/m^3, a bulk modulus of 2.2 10^9 Pa, and dynamic viscosity of 10^{-3} Pa.sec. In the numerical analyses five different baffle elevations are used: h/d= 0.5, 0.6, 0.7, 0.8 and 0.9, where h is the baffle elevation above the base of the tank. The baffle length, L, is also varied as L/a = 0.05, 0.075, 0.1, 0.15 and 0.2.

The minimum number of earthquake records for the time history analysis of structures is specified in seismic design codes. If three time histories are used, design should be carried out for the maximum response obtained from these three time history analyses. If seven records are used an average from the results of seven time history analyses should be used in design. Therefore, in this work, seven accelerograms which are obtained from Pacific Earthquake Engineering Research (PEER) Center, NGA strong motion data base [8] are selected to use in the time history analysis of baffled tanks. First, 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.

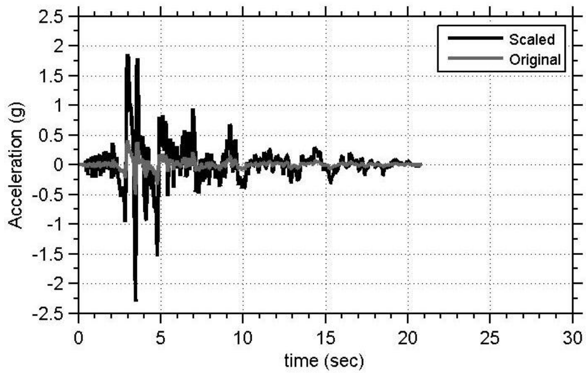
Tab. 3: Earthquake records for the time history analysis of 2D rigid baffled tanks

	Earthquake	Moment Magnitude	Station	Component	Epicentral dist (km)	Shortest dist (km)	Soil type (NEHRP)	Scale Factor
Eq 1	Dinar 01.10.1995	6.4	Dinar	DIN180.AT2	0.44	3.36	D	6.64
Eq 2	Erzincan 13.03.1992	6.7	Erzincan	ERZ-EW.AT2	8.97	4.38	D	4.62
Eq 3	Düzce 12.11.1999	7.1	Duzce	DZC270.AT2	1.61	6.58	D	1.99
Eq 4	Kocaeli 17.08.1999	7.5	Izmit	IZT180.AT2	5.31	7.21	B	5.67
Eq 5	Kocaeli 17.08.1999	7.5	Gebze	GBZ270.AT2	47.03	10.92	B	7.03
Eq 6	Kocaeli 17.08.1999	7.5	Arcelik	ARC090.AT2	53.68	13.49	C	5.17
Eq 7	Kocaeli 17.08.1999	7.5	Iznik	IZN180.AT2	39.82	30.74	D	15.21

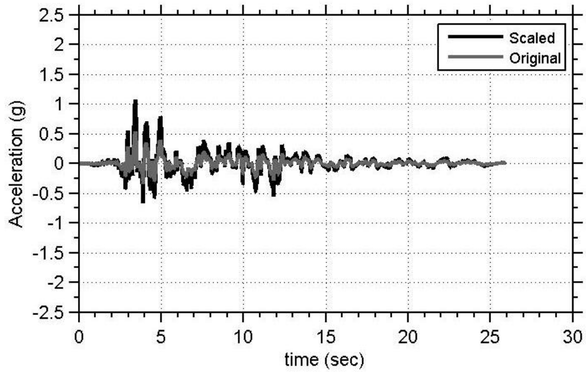
The efficiency of baffles on supressing the sloshing response of tanks can be better quantified by comparing the maximum wave height in baffled tanks with that of un-baffle tanks. Therefore, following the numerical analyses, an average value of the maximum sloshing wave height due to seven different earthquakes is obtained for each h/d and L/a combinations. The average maximum sloshing wave height in un-baffled tall and broad tanks is also numerically predicted. The average maximum sloshing wave height for each h/d and L/a baffle combinations is finally normalised with the average maximum wave height of un-baffled tanks. Fig. 8 and Fig. 9 show the normalized maximum sloshing wave height for tall and broad tanks, respectively. As can be observed from these figures, for some certain baffle combinations (h/d and L/a) normalized wave height is higher than 1. Therefore, some baffle positions can cause amplification in response. This amplification is possibly caused by the interaction between large baffle deformations. Analysis results of the broad and tall tanks show that the most efficient baffle length is 0.10a while the most efficient baffle elevation is 0.9d for both tank types.



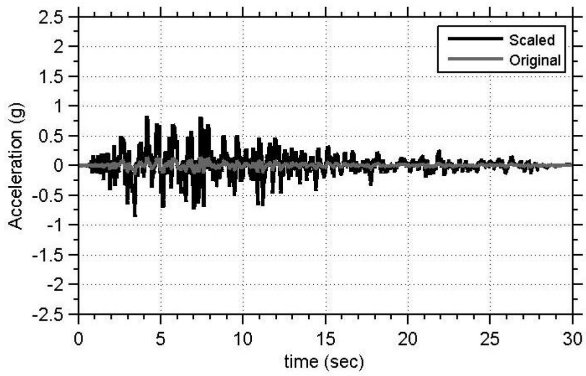
Eq 1



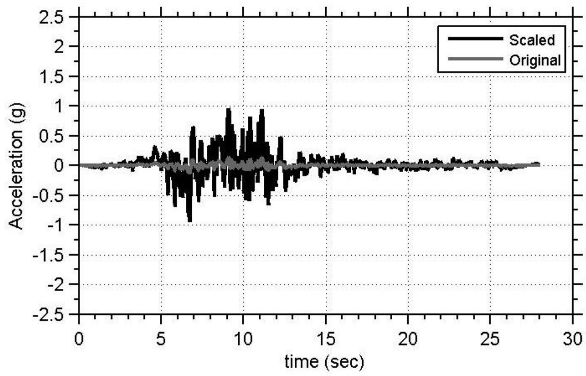
Eq 2



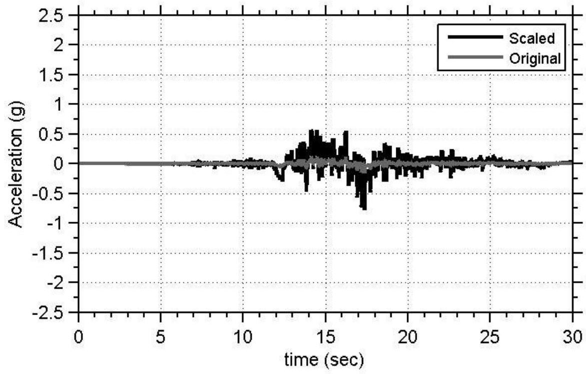
Eq 3



Eq 4



Eq 5



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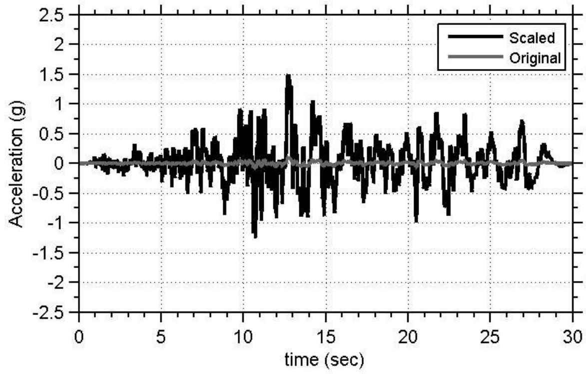

Eq 7

Fig. 7: Scaled earthquake records for the time history analysis of 2D rigid baffled tanks

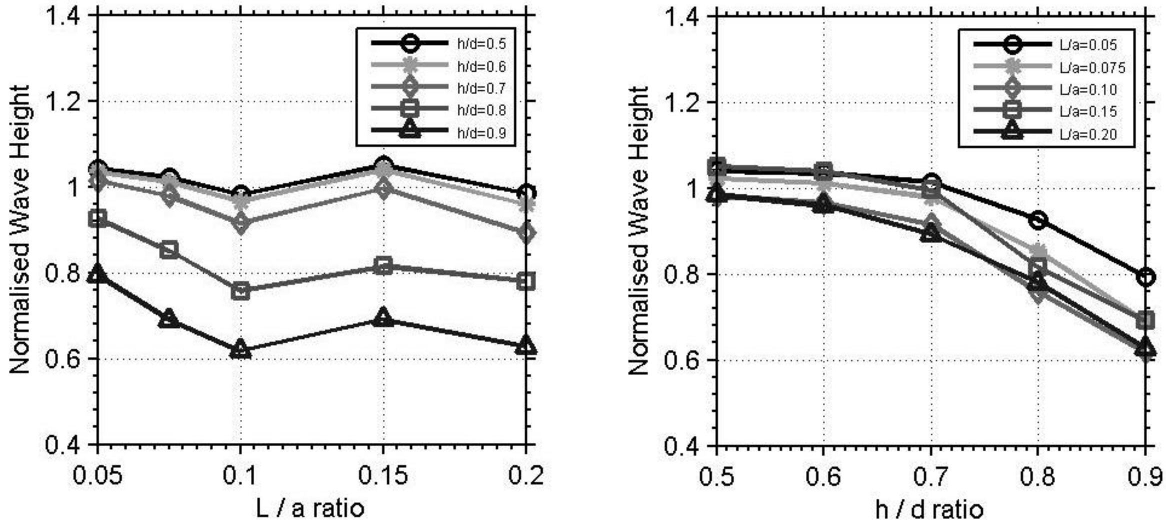

Fig. 8: The normalised average maximum sloshing wave height in Tank I (2a=10.0 m and d=10 m) when subjected to various earthquake motions

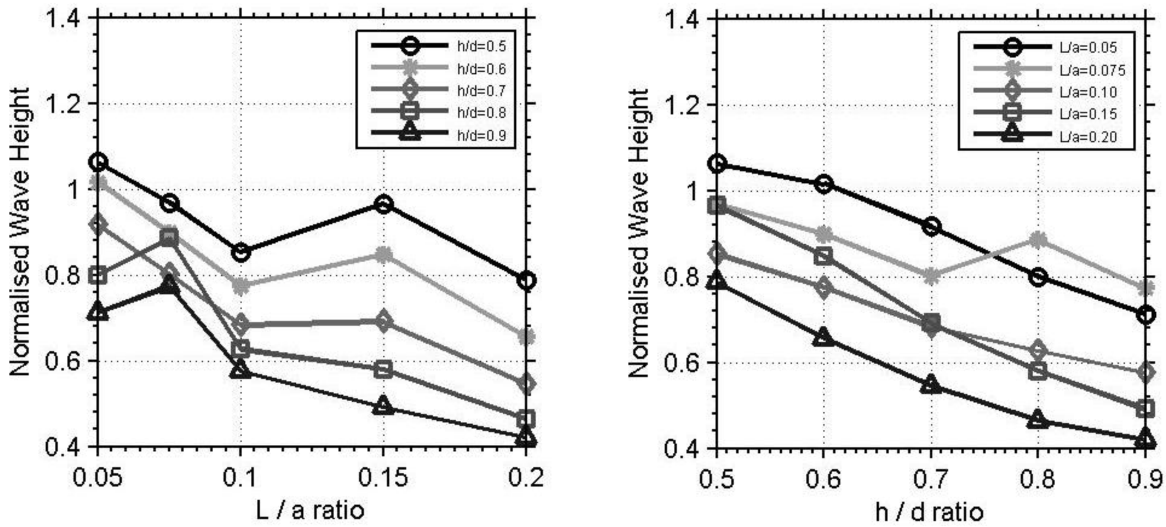

Fig. 9: The normalised average maximum sloshing wave height in Tank II (2a=40.0 m and d=10 m) when subjected to various earthquake motions

5 Conclusions

In current practice, baffles are widely used as passive sloshing suppression devices in order reduce hydrodynamic forces acting on tanks. In this work, sloshing response of 2D rigid baffled tanks is evaluated using a numerical model. A fully nonlinear FSI for the FEM is employed for the computation of interaction forces at the interface of the two materials. Both harmonic and earthquake motions are considered in the numerical simulations. First, the numerical model is verified for a 2D rigid tank when subjected to harmonic motion. Then, a parametric study is undertaken in order to assess seismic sloshing response of baffled tanks with different baffle positions and baffle lengths. The seismic analysis results show that certain combinations of baffle length and baffle elevation amplify the amplitude of sloshing motion instead of attenuating sloshing response. This will, in turn, increase the hydrodynamic forces acting on the tank. Therefore, particular attention should be paid to design of such structures in order to avoid harmful effects of sloshing on tanks.

6 References

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