The effects of multiple vertical baffles on sloshing phenomenon in rectangular tanks

M. Hosseini[1] & P. Farshadmanesh[2]
[1]Graduate School of Civil Eng. Dept., South Tehran Branch of the Islamic Azad University (IAU), Tehran, Iran
[2]Hydraulic Structures Group, Civil Eng. Dept., South Tehran Branch of the Islamic Azad University (IAU),Tehran, Iran

Abstract

One of the phenomena in storage tanks subjected to earthquake excitations is the sloshing of impounded liquid. The use of baffles for reducing the sloshing effects has been taken into consideration by some researchers in recent years, however, the use of multiple baffles has not been taken into consideration so much. In this study the effect of using multiple vertical baffles in rectangular tanks has been investigated numerically by Finite Element Analyses. After verification of the numerical modeling, tanks with various scales were analyzed subjected to both harmonic and seismic excitations with various intensities to find out the effect of scaling factor. Then, various number of vertical baffles form 1 to 4, were considered at the upper level of the tank and analyses were repeated to realize the effect of baffles on the sloshing. The maximum water level fluctuation was calculated for comparison. Different values were also considered for the submerged depth of baffles to find the more effective depth in decreasing the sloshing effect. Numerical results show that for each series of earthquakes with similar frequency content it is possible to find an optimal number of baffles to minimize the sloshing effect. Also for each number of baffles it is possible to find an optimal submerged depth of baffles for minimizing the sloshing effect.
Keywords: water level fluctuation, scaling factor, hydro-dynamic pressure, THA.

1 Introduction

In tanks subjected to earthquake excitations sloshing of liquid is one of the most important phenomena, and past earthquakes have shown that this phenomenon

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can result in sever damages to water storage tanks. To prevent tanks against sloshing induced damages, the use of baffles have been suggested and studied by some researchers since mid 60s [1], however, just few studies have been conducted on using baffles for reducing the earthquake induced sloshing effects.

Shaaban and Nash [2], as one of the first works in this regard, in 1977 studied on response of partially filled liquid-storage circular cylindrical tank with or without an interior cylindrical baffle under seismic actions using Finite Element (FE) technique. They worked on an elastic cylindrical liquid storage tank attached to a rigid base slab. Their studied tank was either empty or filled to an arbitrary depth with an in-viscid, incompressible liquid. They presented a FE analysis for both tank and liquid, to investigate the free vibration of the coupled system permitting determination of natural frequencies and associated mode shapes. They employed Sanders shell theory to express the strain-displacements relationship in the derivation of the shell FE. They determined the response of the tank to artificial earthquake excitation, and performed similar investigations with the addition of an elastic cylindrical perforated baffle to control the system natural frequencies.

In 1999 Gedikli and Ergüven [3] worked on the seismic analysis of a liquid storage cylindrical tank with a rigid baffle. In that study the fluid was assumed to be incompressible and in-viscid, and its motion was assumed to be ir-rotational. They implemented method of superposition of modes to compute the seismic response, and used the boundary element method to evaluate the natural modes of liquid in the tank. In that study the linearized free surface conditions was taken into consideration.

In 2000 Yasuki and his colleagues [4] conducted a study on suppression of seismic sloshing in cylindrical tanks with baffle plates. The purpose of that study was proposing the evaluation model of damping characteristics of cylindrical tank with ring baffle plates. They carried out shaking table tests, in which the location and geometry of the baffle plates were varied, with sinusoidal excitation. Their experimental results showed that the damping characteristic is dependent on the location and geometry of baffle plates. Their model for solid baffle plates was extended to be applicable to both solid and perforated baffle plates, and the validity of their evaluation model was confirmed with the experimental results.

In 2007 Maleki and Ziyaeifar [5] conducted a study on damping enhancement of seismic isolated cylindrical liquid storage tanks using baffles. At first, they analyzed the velocity contours in a cylindrical tank to determine the most effective shape of baffle. Then, they determined the damping coefficients analytically for horizontal ring shape and vertical blade shape baffles. To estimate the sloshing height level and the damping ratio, they developed a methodology, based on Tank Body Spectra, in which the higher sloshing amplitude and the relative fluid velocity with respect to baffles in base isolated tanks are taken into consideration. The results of that study show that the average damping ratio of sloshing mode due to ring baffle increases with a decrease in liquid height and highest damping may be achieved for height to radius ratios of 1.0 to 1.5.

Finally in 2010 Wu [6] conducted a thorough study the nonlinear liquid sloshing in a 3D tank with baffles, in which the mechanism of liquid sloshing and the interaction between the fluid and internal structures were investigated. He applied a developed 3D time-independent finite difference method to solve liquid sloshing in tanks with or without the influence of baffles under the ground motion of six-degrees of freedom. He solved the 3D Navier-Stokes equations and transformed to a tank-fixed coordinate system, and considered the fully nonlinear kinematic and dynamic free surface boundary conditions for fluid sloshing in a rectangular tank with a square base. In that study the fluid was assumed incompressible. The complicated interaction in the vicinity of the fluid-structure interface was solved by implementing one dimensional ghost cell approach and the stretching grid technique near the fluid-structure boundaries were used to catch the detailed evolution of local flow field. A PC-cluster was established by linking several single computers to reduce the computational times due to the implementation of the 3D numerical model.

It is seen in the review of the literature that the analysis of baffled tanks in general is very complicated and time consuming, even with just one or two baffle(s). That is possibly why the use of multiple baffles has not been studied so much. In this study the effect of using multiple vertical baffles on sloshing phenomenon in rectangular tanks has been investigated based on conducting several dynamic analysis cases, by using a powerful Finite Element Analysis (FEA) program. The tanks considered for the study, and the details of analyses cases are discussed in the following sections of the paper.

2 Features of the tanks considered for the study

In this study the typical double-compartment aboveground water tanks, used in water supply system in Iran, were used. The general geometric features of the tanks, considered for the study, are shown in Figure 1.

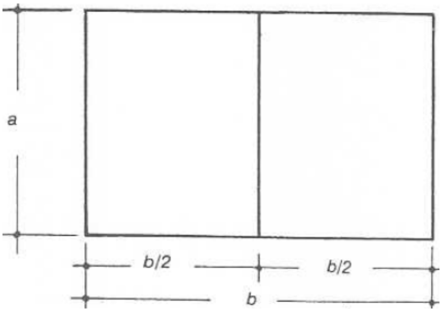


Figure 1: General geometric plan features of the double-containment tanks considered for the study.

To have the minimum length of the tank's wall (to minimize the amount of required construction materials) for a given tank's area, in the case of double-compartment tanks shown in Figure 6, it can be shown easily that *b* should be around 1.5a. Also usually the water depth in the tank, h, is considered not to be less than 0.1 of the width, a, and not more than 6 meters. The common specifications of tanks with different water volumes or capacities, based on the above conditions, are as shown in Table 1.

Table 1: Common specifications of tanks with different water volumes, and their fundamental sloshing period.

The tank water capacity (m^3)	Tank water height, *h*, in the tank (m)	a (m)	*b*=1.5a	*h*/a	*h/b*	*T* (sec)
125	3.0	5.270	7.905	0.758	0.569	2.619
250	3.0	7.453	11.180	0.536	0.402	3.197
500	3.0	10.540	15.811	0.379	0.284	4.029
1000	3.0	14.907	22.360	0.268	0.201	5.270
5000	4.0	28.867	43.301	0.184	0.138	8.408
10000	5.0	36.514	54.772	0.182	0.136	9.502
15000	5.5	42.640	63.960	0.171	0.128	10.523
20000	5.5	49.236	73.854	0.148	0.111	12.019
30000	6.0	57.735	86.602	0.138	0.103	13.434

The values of the first or fundamental sloshing modes of tanks in Table 1 have been calculated based on the following formula which gives the natural angular frequencies of sloshing modes in tanks [8]:

$$\omega_n^2 = \pi(2n-1)\left(\frac{g}{a}\right) tanh\,[(\pi(2n-1)\left(\frac{h}{a}\right)] \tag{1}$$

where n is the sloshing mode number and g in the acceleration of gravity. Based on the above explanations, and considering the exponentially growth of the required computational time with number of elements in the FEA, on the one hand, and the time step size in the time history analysis, on the other, explained in the next section of the paper, in this study the following values were considered as the basic case of the tank for analyses:

a = 1.00 m
b = 1.50 m
h = 0.15 m

By using some appropriate scaling factors these dimensions can be used for tanks of real size, such as those given in Table 1. The scaling requirements are explained in the following section, after the explanation about the finite element modeling and its verification. along with the presentation of numerical results.

3 Finite element modeling and its verification - scaling effects

A powerful FEA program was selected for modeling the tanks in this study. In order to verify the numerical modeling of the tanks in FEA at first the numerical finite element model of a tank, previously tested at the Hydraulic Institute of Stuttgart University on shake table by Goudarzi and his colleagues (results were published in 2010 [7]), was developed by the employed computer program, and the results were compared. Verification results can be found in a previous work of the authors [8], and include the cases of sinusoidal base excitations at the first sloshing mode (resonance), and also a frequency lower the resonance frequency. Another important factor, which affects the required time for the response analysis, is the size of the tank [8]. In fact, the required analysis time for a scaled-down model of a tank is several times less than that of the real tank. The main reason behind this fact is in the size of the time step for analysis of a scaled-down tank. Actually, considering that based on Equation (1) the sloshing frequencies vary inversely with variation of the square root of the tank's length, shown in the equation by 'a', it can be easily seen that the sloshing period in a scaled model, T_m, is related to the sloshing period in the prototype tank, T_p, by:

$$\frac{T_m}{T_p} = \sqrt{\frac{L_m}{L_p}} \tag{2}$$

where L_m and L_p are respectively the length of the scaled model tank and that of the prototype tank. On this basis, it is clear that the sloshing period in a scaled-down model with the length of 1/36 (for example) of the real size tank will be 6 times shorter than the sloshing period in the prototype tank. This means that the size of the time step of the earthquake digitized record, considered for analyzing the scaled-down model, should be also scaled down by the same factor of 6 to keep the proportions of the excitation periods with respect to the sloshing period in the prototype tank. Accordingly, the duration of the record, used for the scaled-down model, will be 6 time shorter than the real record, although the number of time steps is the same as the original record. It is clear that using a much shorter time step in time history analysis leads to much higher convergence rate, which in turn, reduces the required analysis time to a great extent. On this basis, it was decided in this study to use a scaled-down model tank with the length of 1.0 meter, which is almost 1/36 of a tank with 10000 m^3 capacity, as shown in Table 1. This capacity relates to a very common set of tank features, as shown in table 1, with 5.0 m water height, and plan dimensions of 36.5 m by 54.8 m. In the 1/36 scaled-down model with 1.00 meter length and of 0.15 meter water height, the periods of the first three modes can be calculated based on the corresponding natural frequencies given by Equation (1) in previous section. Their values are respectively 1.708, 0.693, and 0.511 seconds.

The last points which should be taken into consideration for increasing the speed of FEA are the width of the tank model. Regarding that in this study the effects of using multiple vertical baffles is the main concern; the base excitation and accordingly the induced sloshing have been assumed to occur in just one main direction of the tank length. On this basis, it was important to know if the tank's width, which is the dimension in direction perpendicular to the excitation direction, does have any effect on the analyses results. For this purpose various values were considered for the parameter *b* and by using a specific excitation the analysis was repeated, of which the results are shown in Figure 2.

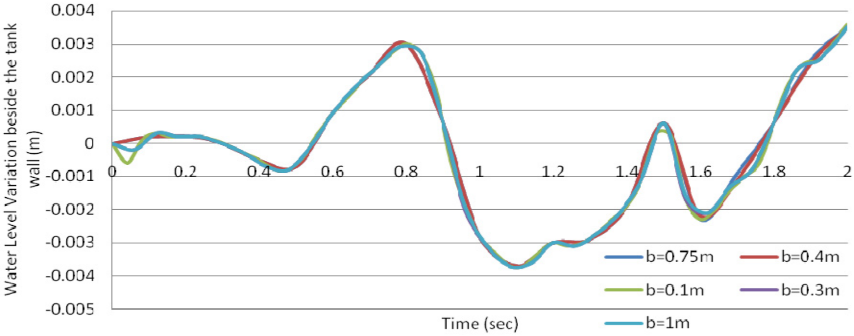


Figure 2: Effect of the width of the tank model on the water level variation when excitation is along the tank's length.

Figure 2 indicates that, as long as the excitation is just in one main direction of the tank plan, the tank dimension perpendicular to the excitation direction does not have any major effect on the response values. On this basis, in all of the next analyses cases, a constant value of 0.1 m was used for the width of the tank model, as shown in Figure 3, to reduce the time required for the analyses.

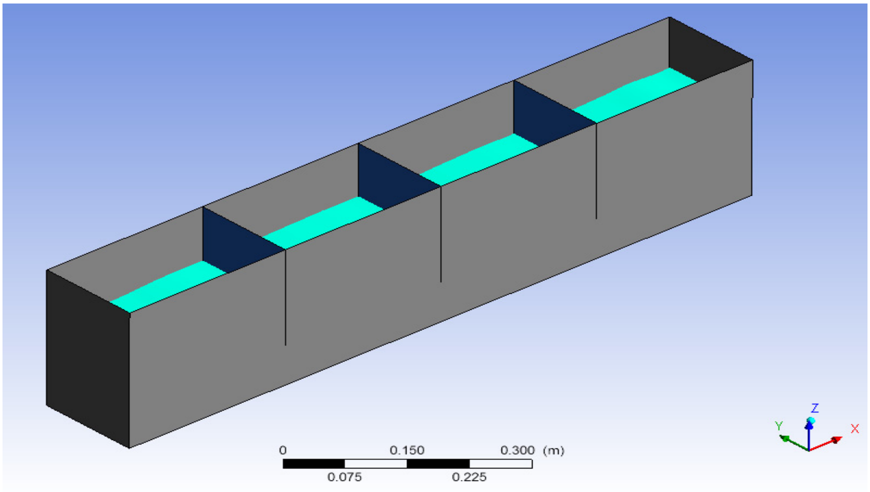


Figure 3: A 3-baffle tank model with reduced width to decrease the time required for FEA.

4 Sloshing response to harmonic base excitations

The first set of dynamic response analyses of the modeled tanks is related to the sloshing response to base harmonic excitation with constant amplitude having the form of $u_b(t) = u_0 sin\omega t, u_0 = 5\ mm$ with the frequency of each of the first 3 sloshing modes. Figure 8 shows a sample of the water surface profile in the case of excitation with the 1st sloshing mode frequency, when various number of baffles are used. In case of using just one baffle it has been considered to be at the middle of the tank's length, and in cases of using 2, 3, or 4 baffles they have been considered equally spaced, so that the tank's length have been divided accordingly into 3, 4, or 5 parts of equal lengths. Figures 4 to 6 show the maximum water level variation beside the tank wall in cases of harmonic excitation with the frequency of respectively the 1st, the 2nd, and the 3rd sloshing mode in the tank, when using no, 1, 2, 3, or 4 baffle(s).

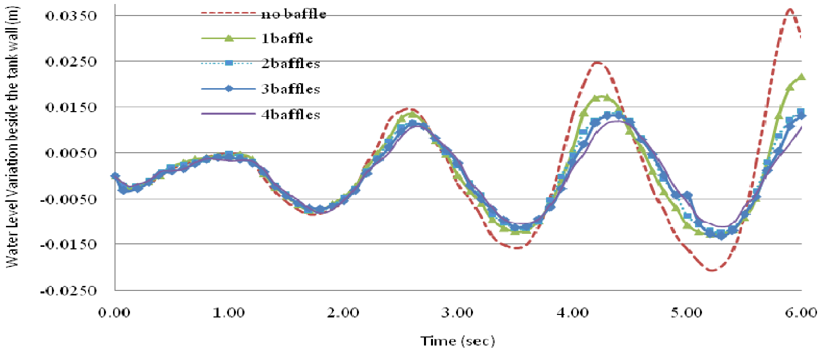


Figure 4: Water level variation beside the tank wall in the first sloshing mode with various numbers of baffles.

It can be seen in Figure 4 that using more vertical baffles results in more reduction in the maximum water level variation, when the excitation frequency is equal to the frequency of the first sloshing mode. Figure 5 shows that when the excitation frequency is equal to that of the second sloshing mode, using two baffles leads to increase, rather than decrease, of the maximum water level variation comparing with the case of using no baffle, however, the maximum water level variation is less than its values in the case of excitation with the first sloshing mode frequency. Also, Figure 5 shows that when the excitation frequency is equal to that of the third sloshing mode, using more baffles again results in more increase in the maximum water level variation comparing with the case of using no baffle, however, the maximum water level variation is less than its value in the case of excitations with the first and second sloshing mode frequencies. Furthermore, comparing Figures 4 to 6 it can be observed that the rate of increase in the maximum amplitude of water level variations, and reaching its steady state response increases with increasing the excitation frequency. This implies that the water body shows larger values of damping when it is subjected to higher frequency excitations. After realizing the effects of using multiple vertical baffles in sloshing response to harmonic excitations, by considering some appropriate earthquake records the sloshing response to seismic excitations, and the effect of using multiple vertical baffles in that case was studied, as explained in the next section of the paper.

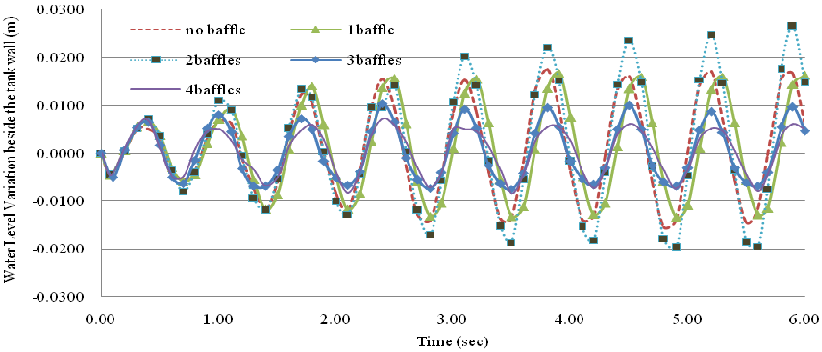


Figure 5: Water level variation beside the tank wall in the second sloshing mode with various numbers of baffles.

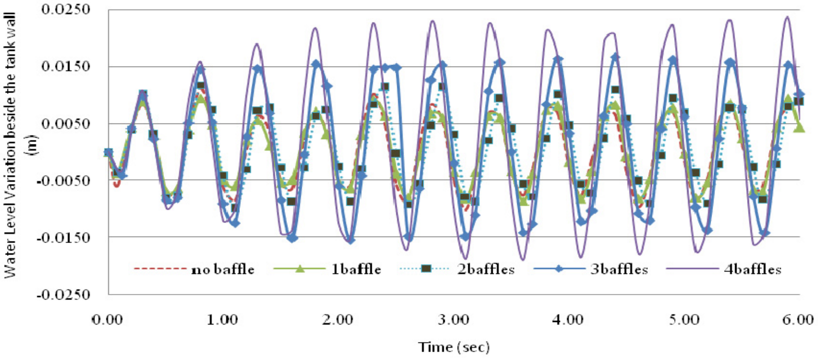
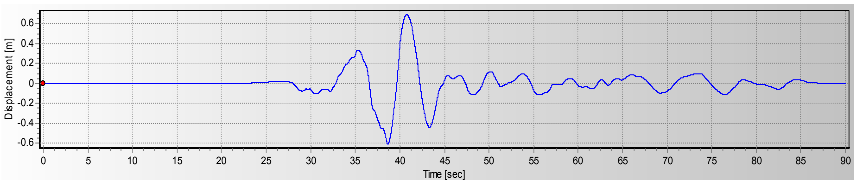


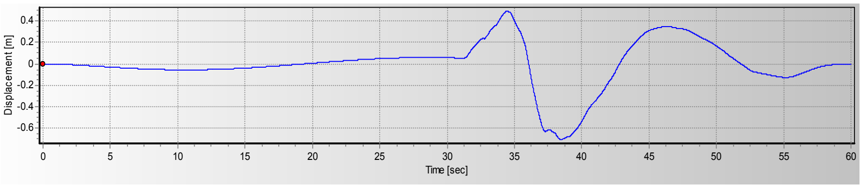
Figure 6: Water level variation beside the tank wall in the third sloshing mode with various numbers of baffles.

5 Sloshing response to seismic base excitations

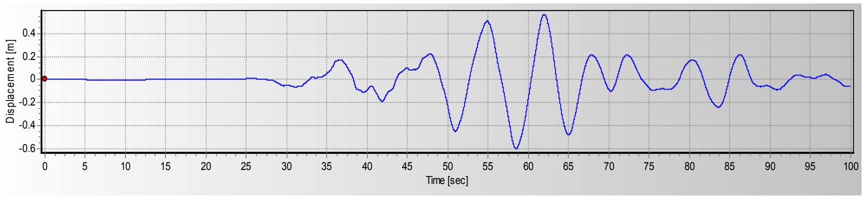
To investigate the effect of using multiple vertical baffles in the sloshing response in tanks, when subjected to seismic excitations, some earthquake records were considered based on their frequency content, and were applied with various scales. The earthquake records were selected by considering the sloshing frequencies of tanks with real size, which are generally low, for tanks with common sizes, which as shown in Table 1, have sloshing periods in range of 2.5 to 13.5 seconds. Among the available earthquakes, San Fernando earthquake of 1971, Tabas, Iran earthquake of 1978, Northridge earthquake of 1994, Chi-Chi, Taiwan earthquake of 1999, and Kocaeli earthquake of 1999 were considered.



(a) Chi-Chi earthquake (Chy101N record)



(b) Kocaeli earthquake (Sakarya record)



(c) Chi-Chi earthquake (Chy59 record)

Figure 7: The displacement histories of some of the selected earthquakes.

All of the selected records have long period oscillations in their displacement history in the period range of 2.5 to 10 seconds, as it can be seen in Figure 7.

The displacement histories of these earthquakes, when scaled-down in time by a factor of 1/6, as explained in the previous section, have displacement oscillations in the period range of around 0.5 to 1.5 seconds. To reduce the required analysis time, only the 3 to 6 seconds of the strong ground motion parts of the scaled records, containing about 4 to 12 major oscillations, were used in time history analyses. As mentioned before, the variation of water level beside either the tank wall or the baffle(s) is a good response value for studying the sloshing phenomenon and the effect of using baffles on it. These variations, corresponding to scaled versions of some of the aforementioned records, shown in Figure 7, obtained by using the scaled-down tank models, in case of using no baffle comparing to the cases of using 1, 2 or 3 baffles are presented in Figures 8 to 10. More results cannot be given here because of lack of space, and can be found in the main report of the study [9].

It is seen in Figures 6 to 8 that using baffles generally leads to decrease in the water level variations (the maximum water rising), and using more baffles results in more decrease in water level rising. However, similar analyses by using other earthquake records, such as San Fernando, Tabas, and Northridge showed that using more than 3, and in some cases 2, baffles does not change the results so

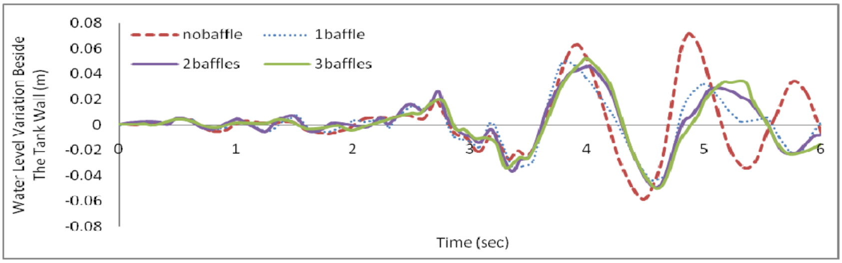


Figure 8: The water level variations beside the wall of 1/15 scaled-down 250 m^3 tank with no, 1, 2, and 3 baffle(s) subjected to the scaled record of Chi-Chi earthquake (Chy101N record).

much. Therefore, it can be recommended that 2 baffles are used in tanks of the sizes around the size of the studied tanks.

The other studied issue was the effect of the submerged depth of the baffle in the sloshing response. For this purpose a tank of 70 cm length and 20 cm width with 50 cm water depth, with just one baffle, subjected to a sinusoidal base motion of $u_b(t) = u_0 sin\omega t, u_0 = 20\ mm\ and\ \omega = 6.55$ (the resonance case) was considered (Figure 9).

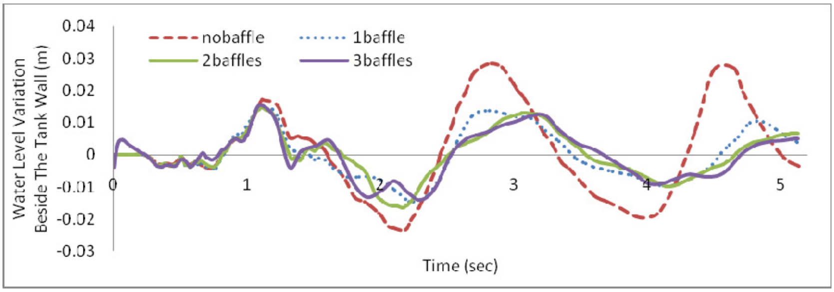


Figure 9: The water level variations beside the wall of 1/36 scaled-down 10000 m^3 tank with no, 1, 2, and 3 baffle(s) subjected to the scaled record of Kocaeli earthquake (Sakarya record).

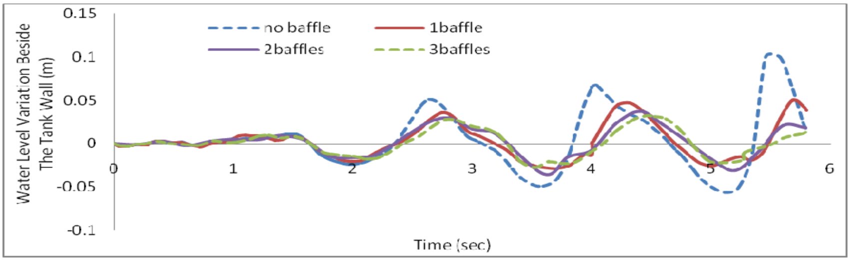


Figure 10: The water level variations beside the wall of 1/20 scaled-down 1000 m^3 tank with no, 1, 2, and 3 baffle(s) subjected to the scaled record of Chi-Chi earthquake (Chy59 record).

Four values were used for the submerged depth of the baffle. The results can be seen in Figure 10.

It is seen in Figure 10 that using a baffle submerged depth of more than 20 cm does not change the maximum water level variations. Therefore, it is recommend to use an optimal submerged baffle depth in each tank based on its geometric features and water depth.

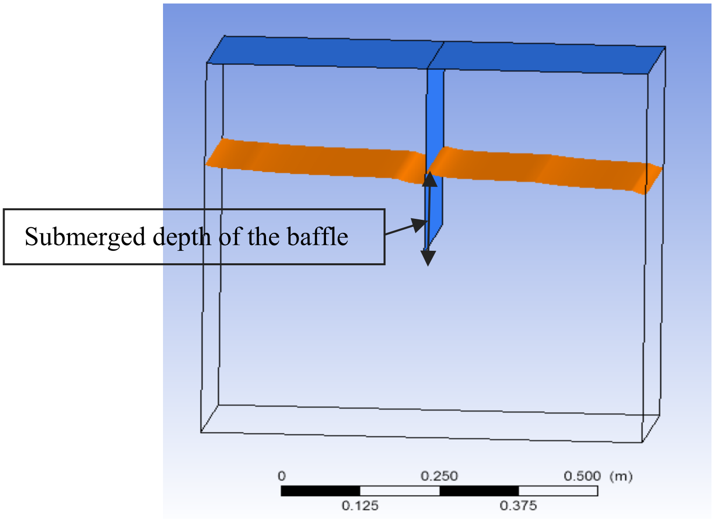


Figure 11: Considered tank for studying the effect of the baffle submerged depth.

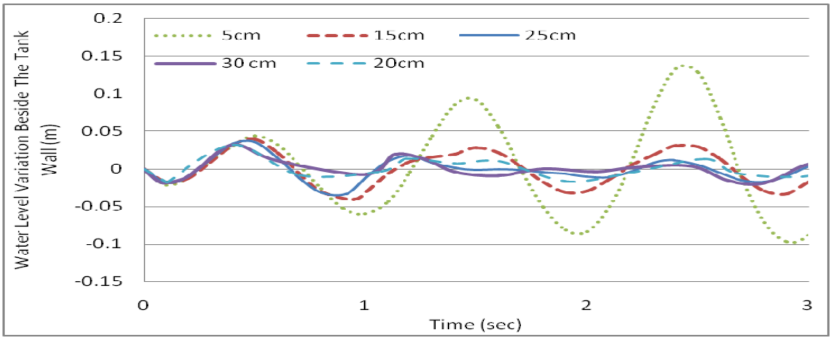


Figure 12: The effect of the baffle submerged depth on the sloshing response.

6 Conclusions

Based on the numerical results of this study it can be concluded that:

- Using scaled down numerical models of tanks, which results in shorter time steps, and accordingly shorter durations, for time history analyses lead to significant reduction of the required analysis time.

- When the excitation is in one of the main directions of the tank, the width of tank model can be chosen as small as 10 cm. This also will lead to reduction of the required analysis time.
- Using 2 or 3 vertical baffles, equally spaced along the tank's length, can reduce the sloshing effect to a great extent, and using more baffles does not change the results so much.
- Using an optimal submerged depth for the baffles is possible, and it depends on the geometric features the tank and the water depth.

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