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SIMPLIFIED DYNAMIC ANALYSIS OF SLOSHING PHENOMENON IN TANKS WITH MULTIPLE BAFFLES SUBJECTED TO EARTHQUAKE

Mahmood Hosseini[1] **and Pegah Farshadmanesh**[2*]

[1] Structural Eng. Research Center, Int'l Institute of Earthquake Engineering and Seismology (IIEES)
No. 21 Arghavan, North Dibaji St., Farmanieh, Tehran 19537, Iran
hosseini@iiees.ac.ir

[2] Hydraulic Eng. Group, Civil Eng. Dept., Tehran South Branch of the Islamic Azad University (IAU)
Ahang Blvd, Tehran, Iran
(p.farshadmanesh@gmail.com)

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Abstract. *Sloshing is a well-known phenomenon in liquid storage tanks subjected to base or body motions. In recent years the use of baffles for reducing the sloshing effects in tanks subjected to earthquake has been studied by some researchers. However, the use of multiple baffles has not been taken into consideration so much. On the other hand, although some of the existing computer programs are capable to model sloshing phenomenon by acceptable accuracy, the full dynamic analysis subjected to random excitations such as earthquake induced motions is very time consuming, particularly when there are vertical and horizontal baffles inside the tank, which postpone the convergence of response calculations. Therefore, a simplified method for evaluation of sloshing effects in baffled tanks is desired. In this paper a method is presented for this purpose based on conducting several dynamic analysis cases, by using a powerful Finite Element (FE) method for rectangular tanks with various dimensions, subjected to both harmonic and seismic excitations, and then using neural network to create simple relationships between the dominant frequency and amplitude of the base excitations and the maximum level of liquid in the tank during the sloshing and also the maximum dynamic pressure on the tank wall. At first, the FE numerical modeling has been verified by using some existing experimental data. Then, dynamic analyses have been conducted to obtain the required numerical results for teaching the neural network. In the next stage, the neural network model has been developed. Finally, the predicted results of the neural network have been compared with those obtained by some other cases of analyses as control values, to make sure on the accuracy of the neural network model. The proposed simplified neural network model can be used also for finding the proper number and features of baffles for minimizing the sloshing effect on the tank for a group of given earthquakes, or other cases of base excitations.*

1 INTRODUCTION

One of the most important phenomena in fluid storage tanks, either buried, semi-buried, aboveground or elevated, is the oscillation of fluid due to the movements of the tank body, because of its base motions during an earthquake. Past earthquakes have shown that this phenomenon 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.

As one of the first works in this regard Shaaban and Nash (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 [2]. 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 worked on the seismic analysis of a liquid storage cylindrical tank with a rigid baffle [3]. 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.

Yasuki and his colleagues (2000) conducted a study on suppression of seismic sloshing in cylindrical tanks with baffle plates [4]. 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.

Maleki and Ziyaeifar (2007) conducted a study on damping enhancement of seismic isolated cylindrical liquid storage tanks using baffles [5]. Mentioning that in moving liquid containers, baffles play an important role in damping the liquid motion, to study the effects of using baffles in seismically isolated tanks, in the first instance they have analyzed the velocity contours in a cylindrical tank to determine the most effective shape of baffle. Then they have determined the damping coefficients analytically for horizontal ring shape and vertical blade shape baffles. To estimate the sloshing height level and the damping ratio, Maleki and Ziyaeifar have 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. They have also developed a computer program to put all these together and investigate the effect of baffles for different tank dimensions under the effect of earthquakes. Their results 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. In addition, for reasonable ring baffle dimensions, an average reduction of 6% in base displacement of base isolated tanks and an average reduction of more than 30% in the sloshing height of base isolated and fixed base tanks may be achieved. To study the effect of baffles on the distribution of hydrodynamic and tank body forces with height, Maleki and Ziyaeifar have proposed a simple dynamic model. The results of analyses using this model indicate a constant reduction in sloshing forces and different reductions in moment and shear forces for different heights. This happens because contribution of the sloshing force to the total hydrodynamic force varies with height.

Wu (2010) has 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 have been investigated [6]. He has 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 has solved the 3D Navier-Stokes equations and has transformed to a tank-fixed coordinate system, and has 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. The Message Passing Interface (MPI) parallel language and MPICH2 software were utilized to code the computer codes and to carry out the circumstance of parallel computation, respectively.

Wu has verified his developed numerical scheme by rigorous benchmark tests, and has also performed some further experimental investigations [6]. In that study for a tank without internal structures, the coupled motions of surge and sway were simulated with various excitation angles, excitation frequencies and water depths. The characteristics of sloshing waves were dissected in terms of the classification of sloshing wave types, sloshing amplitude, beating phenomenon, sloshing-induced forces and energy transfer of sloshing waves. Six types of sloshing waves, named single-directional, diagonal, square-like, swirling-like, swirling and irregular waves, were found and classified in Wu’s study and he found that the occurrence of these waves are tightly in connection with the excitation frequency of the tank. The effect of excitation angle on the characteristics of sloshing waves was explored and discussed, especially for swirling waves. In that study the spectral analyses of sloshing displacement of various sloshing waves were examined and a clear evidence of the correlation between sloshing wave patterns and resonant modes of sloshing waves were demonstrated. The mechanism of switching direction of swirling waves was also discussed by investigating the situation of circulatory flow, the instantaneous free surface, the gravitational effect and the instantaneous direction of external forcing.

Wu also considered a 2D tank with vertically tank bottom-mounted baffles and has discussed the influence of baffle height on the natural mode of the tank, the evolution of vortices and vortex shedding phenomenon, the relationship between the vortex shedding frequency and the excitation frequency of the tank, the vortex size generated in the vicinity of the baffle tip, and the interaction of vortices inside the tank [6]. Based on the results the baffle height shows a significant influence on the shift of the first natural frequency of the baffled tank and the liquid depth also plays an important part in determining this influence. In other words, the shift of the first natural mode due to various baffle heights varies with water depths. Wu has claimed that the design of two baffles separated by 0.2 times the tank breadth is an efficient tool to not only reduce the sloshing amplitude, but also switch the first natural frequency of the tank. The results also show that sloshing displacement is affected distinctly by different numbers of baffles mounted vertically on the tank bottom. The more baffles mounted onto the tank bottom, the smaller the sloshing displacement is presented in both the transient and steady-state periods. Wu has categorized the processes of the evolution of vortices near the baffle tip into four phases: the formation of separated shear layer and generation of vortices, the formation of a vertical jet and shedding of vortices, the interaction between shedding vortices and sloshing flow (the generation of snaky flow) and the interaction between snaky flow and sloshing waves. Results show that vortex shedding phenomenon due to stronger vertical jets occurs when the excitation frequency is close to the first natural mode of the baffled tank, and that is discussed and the size of vortex, generated near the baffle tip, is closely correlated with the baffle height. In that study two types of 3D tuned liquid dampers, a vertically tank bottom-mounted baffle and a vertical plate, were discussed for a tank under coupled surge-sway motions. Results show that the wave types of diagonal and single-directional waves switch to the swirling type due to the influence of the baffle. The phenomenon of square-like waves or irregular waves coexisting with swirling waves is found in the baffled tank under diagonal excitation. The shift of the first natural mode of the baffled tank due to various baffle heights is remarkable. The length of the plate can cause a significant influence on not only the variation of the natural frequencies but the type of the sloshing waves. The influence of the vertical plate on the irregular waves is insignificant and several peaks appear in the spectral analysis of the sloshing displacement for the irregular waves and the numbers of peaks are more than that of the baffled tank.

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). It is then clear that multiple baffles make the behavior of the liquid inside the tank more complicated, and accordingly makes the analysis much more difficult and time consuming. In this study a simplified method for evaluation of sloshing effects in rectangular tanks with multiple baffles is presented. The method is based on conducting several dynamic analysis cases, by using a powerful FE method for tanks with various dimensions, subjected to both harmonic and seismic excitations, and the use of neural network to create simple relationships between the dominant frequency and amplitude of the base excitations and the maximum level of liquid in the tank during the sloshing and also the maximum dynamic pressure on the tank wall. The details of the study are discussed in the following section of the paper.

2 FINITE ELEMENT MODELING AND ITS VERIFICATION

In order to verify the numerical modeling of the tanks by FE analysis at first the numerical FE model of a tank, previously tested at the Hydraulic Institute of Stuttgart University on shake table (Figure 1) by some other colleagues (Goudarzi et al. 2010) [7], were developed by the employed computer program.

Figure 1: The scaled-down tank model on the shake-table [7]

The length, height, and width of the liquid volume inside the tank have been respectively 1.00, 0.64, and 0.40 meters. Figures 2 and 4 show experimental, analytical, and numerical results of sloshing in the considered scaled tank model all together, studied by Goudarzi and his colleagues subjected to sinusoidal base excitations $(u_b(t) = u_0 sin\omega t, u_0 = 5\ mm)$ in two cases of, respectively, resonant ($\omega = \omega_N$) and with a lower frequency ($\omega < \omega_N$), and Figures 3 and 5 show the results obtained by the FE model developed in this study.

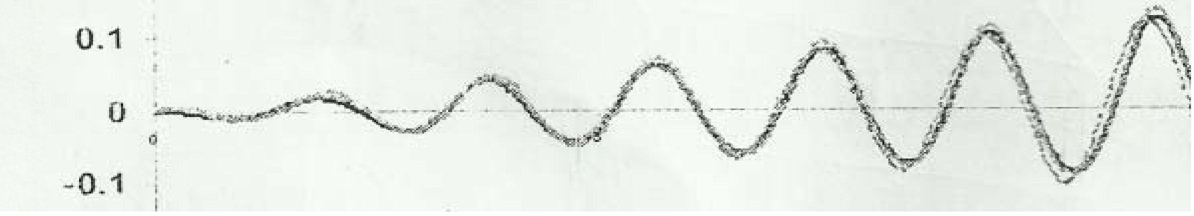

Figure 2: Experimental, analytical and numerical results of sloshing in the tank scaled model subjected to sinusoidal base excitations at resonance [7]

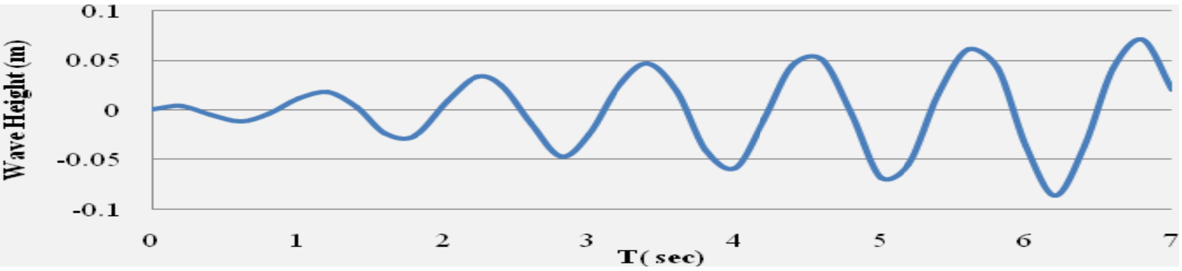

Figure 3: Numerical results obtained by FE analysis of sloshing in the tank scaled model whose experimental and analytical results for sinusoidal base excitations at resonance are shown in Figure 2

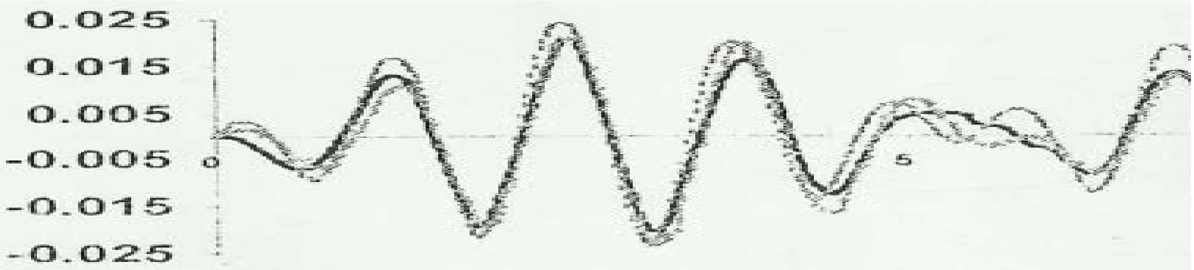

Figure 4: Experimental, analytical, and numerical results of sloshing in the tank scaled model subjected to sinusoidal base motion with $\omega < \omega_N$, [7]

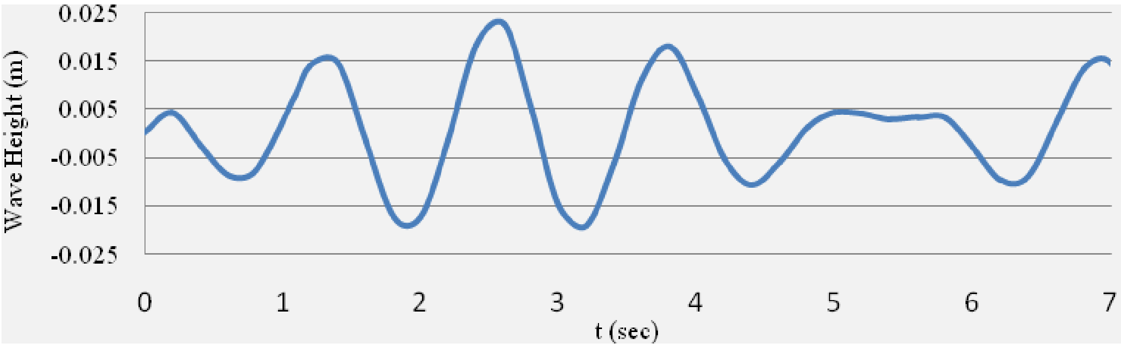

Figure 5: Numerical results obtained by FE analysis of sloshing in the tank scaled model whose experimental and analytical results for sinusoidal base excitations with $\omega < \omega_N$ are shown in Figure 4

Comparing Figure 3 with Figure 2 and also Figure 5 with Figure 4, the very good agreement between the numerical result obtained by the FE model, developed in this study, and the experimental and analytical results can be seen. Based on this verification, the employed FE modeling process could be used for more detailed analysis of sloshing in tanks as explained in next sections.

3 CONSIDERED TANKS FOR THE FINITE ELEMENT ANLYSES

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 6.

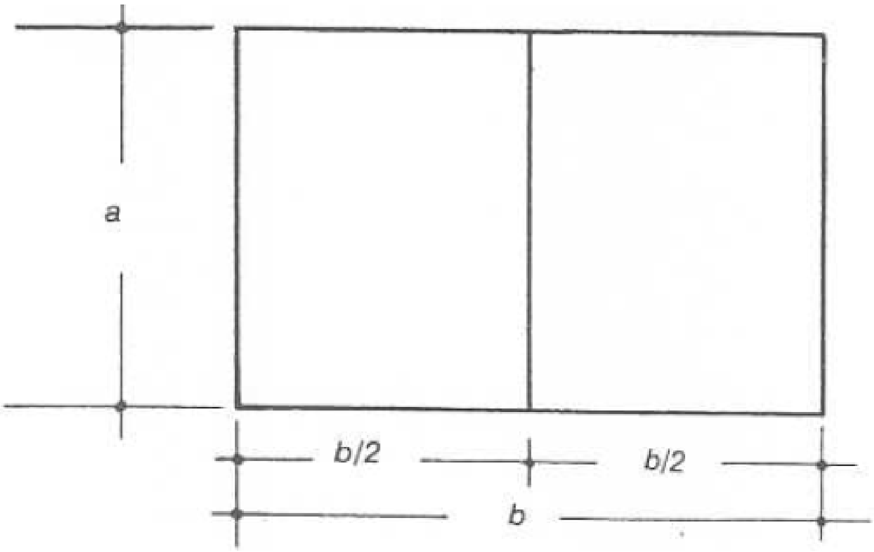

Figure 6: General geometric plan features of the double-containment tanks considered for the study

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 FE analysis, 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, along with the presentation of numerical results.

4 SCALING EFFECTS AND SLOSHING RESPONSE TO HORMONIC BASE EXCITATIONS

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 7.

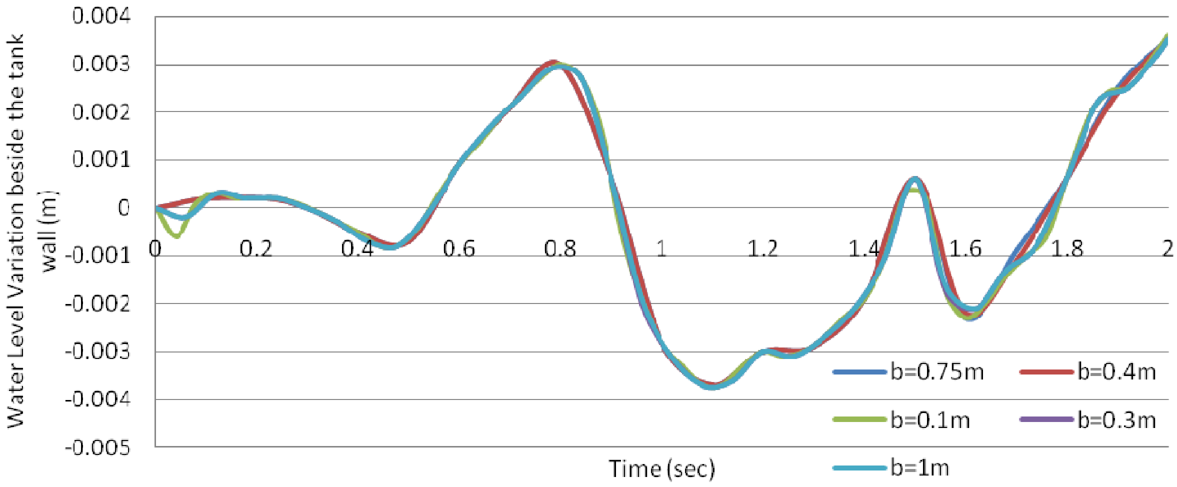

Figure 7: The effect of the tank's width on the water level variation when excitation is along the tank's length

Figure 7 indicate 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 analyses cases, a constant value of 0.1 m (instead of 1.5 m) was used for the tank's width to reduce the required time for the analysis.

Another important factor, which affects the required time for the response analysis, is the size of the tank. In fact, the experience gained in this study showed that 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, which should be used for 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:

$$\frac{T_m}{T_p} = \sqrt{\frac{L_m}{L_p}} \qquad (2)$$

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 m3 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 first set of dynamic response analyses of the modeled tank is related to the base harmonic excitation of 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.

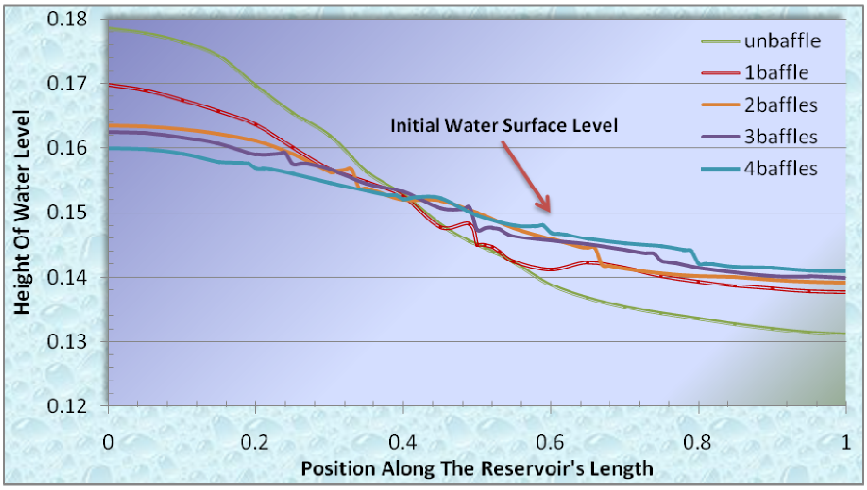

Figure 8: The water surface profile in the time instance of 5.1 seconds in the case of excitation with the 1st sloshing mode frequency when using no, 1, 2, 3, or 4 vertical baffle(s)

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. As in can be seen in Figure 8, there is an abrupt change of water surface elevation at the location of each baffle. Looking at Figure 8 it seems that using more baffles leads to more decrease of the water level rising, however, since Figure 8 is showing only one instant of the time history, to make sure the using more baffles has a decreasing effect on the water level rising at all points along the reservoir's length, the maximum water level beside either the tank's wall or the baffle(s) should be studied. For this purpose the water level variation beside the tank wall was studied first. Figures 9 to 11 show these variations 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).

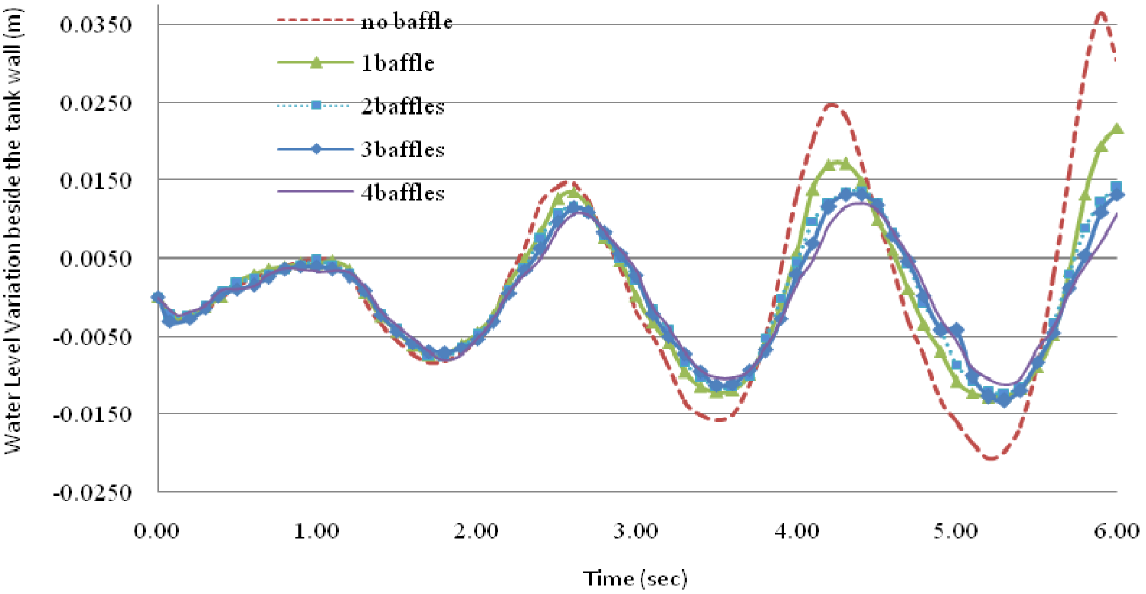

Figure 9: Water level variation beside the tank wall in the first sloshing mode with various number of baffles

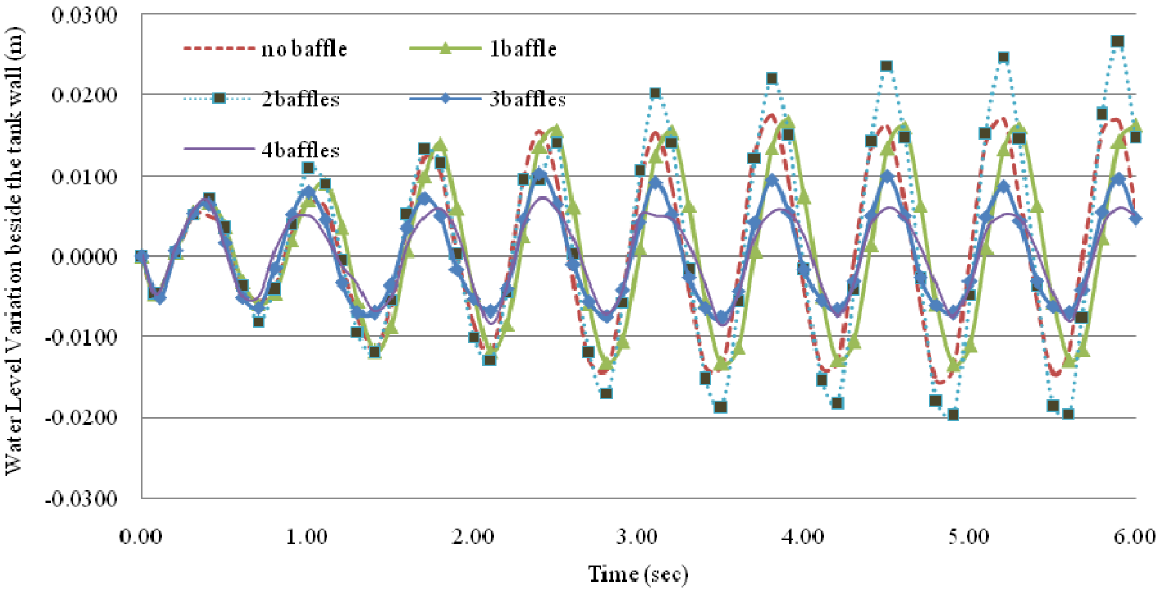

Figure 10: Water level variation beside the tank wall in the second sloshing mode with various number of baffles

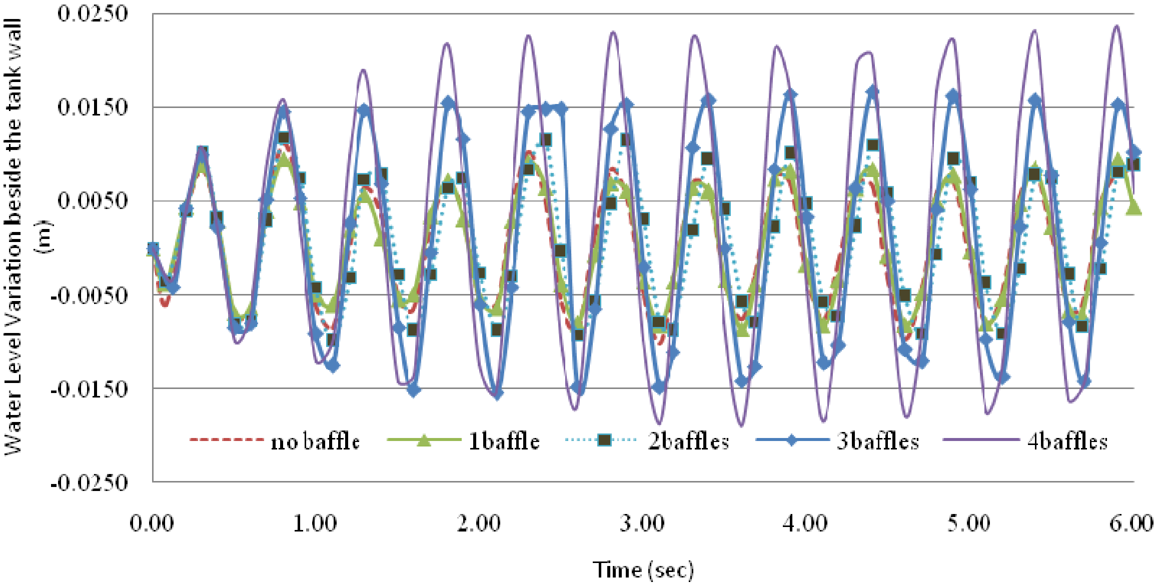

Figure 11: Water level variation beside the tank wall in the third sloshing mode with various number of baffles

It can be seen in Figure 9 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 10 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 10 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 9, 10, and 11 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.

5 SLOSHING RESPONSE TO SEISMIC EXCITATIONS AND THE EFFECT OF USING MULTIPLE VERTICAL BAFFLES

To investigate the effect of using multiple vertical baffles in the sloshing response in tanks, when subjected to seismic excitations, and establishing a reasonable relationship between the baffles' number and their features as well as the seismic excitation's characteristics as the input and the maximum water level variation as well as maximum hydrodynamic pressure on the tank wall, as the output, 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, Chi-Chi (CHY024 component), Taiwan earthquake of 1999, San Fernando earthquake of 1971, and Northridge earthquake of 1994, were selected, whose spectral pseudo velocity curves are shown in Figure 12.

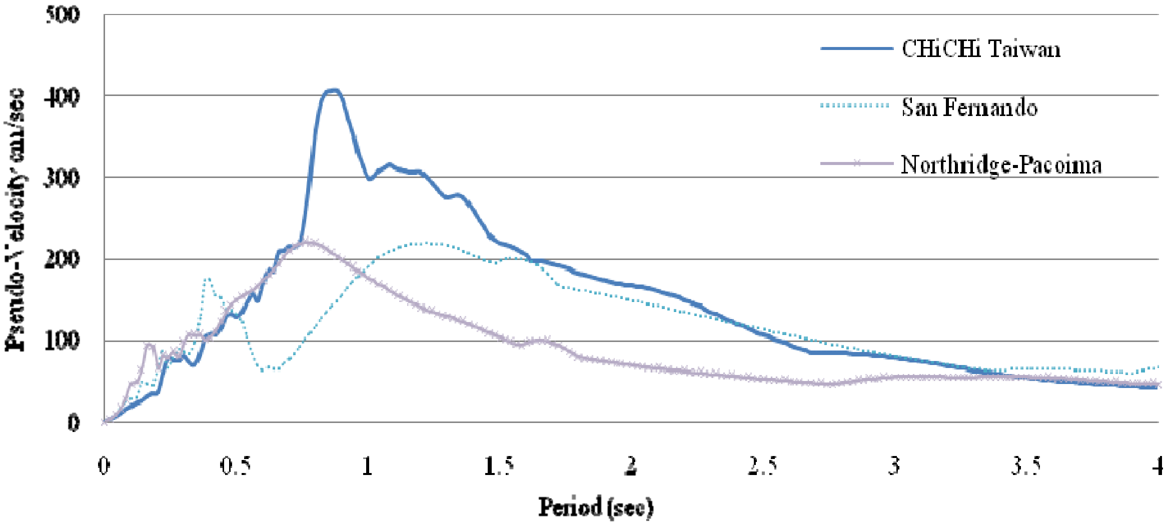

Figure 12: Pseudo-velocity response spectra of the three selected earthquakes for time history analyses

As it is seen in Figure 12, the selected earthquakes have relatively high energy in the range of long periods, and can excite well the sloshing modes in relatively large tanks with sloshing periods of larger than 2.5 seconds. All of these earthquakes have long period oscillations in their displacement history in the period range of 2.5 to 10 seconds. For example, the long period motions of Chi-Chi earthquake, as a sample, can be seen in Figure 13, which shows the displacement time history of this earthquake component.

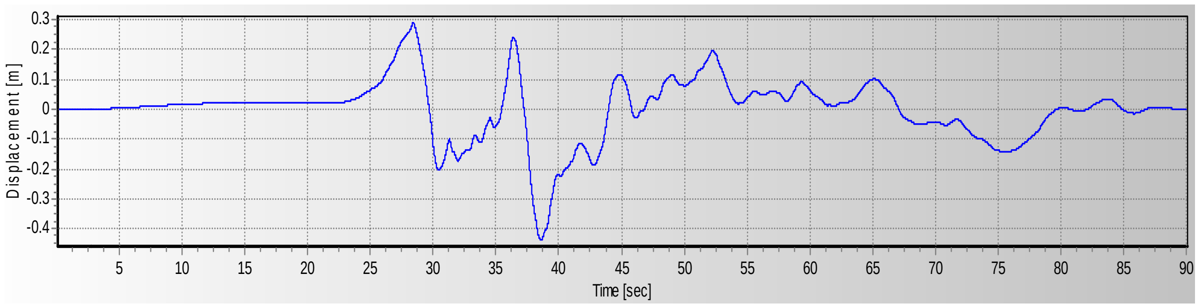

Figure 13: Displacement time history of Chi-Chi earthquake (CHY024 component)

The displacement histories of these earthquakes, when scaled-down 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 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. Therefore, these variations, corresponding to the aforementioned earthquakes, are shown in Figures 14 to 16, which show respectively response to Northridge earthquake in cases of using no baffle comparing to the cases of using 1, 2, or 3 baffles, response to Chi-Chi earthquake in case of using no baffle comparing to the cases of using 2 or 3 baffles, and finally response to San Fernando earthquake in case of using no baffle comparing to the cases of 1 or 3 baffles.

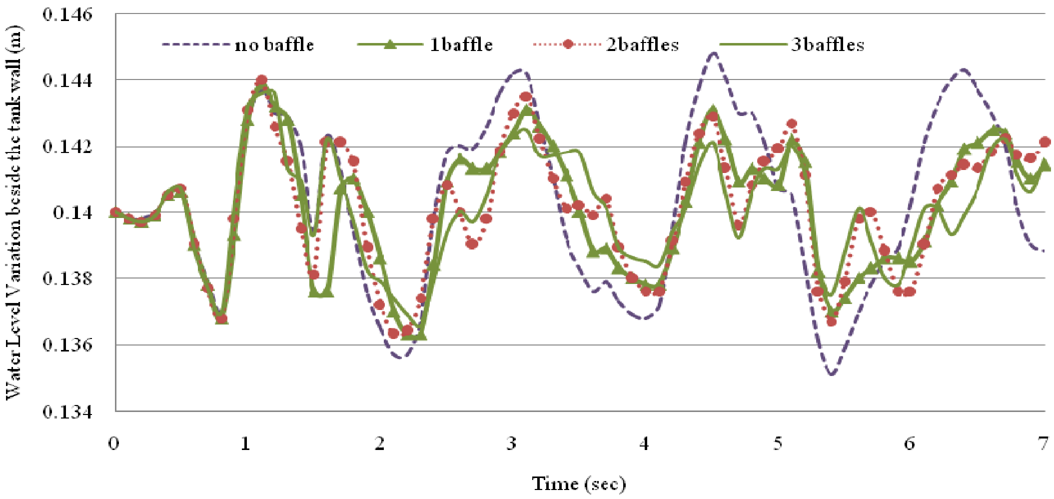

Figure 14: Water level variations beside the tank wall with different number of baffles, when subjected to the scaled Northridge record

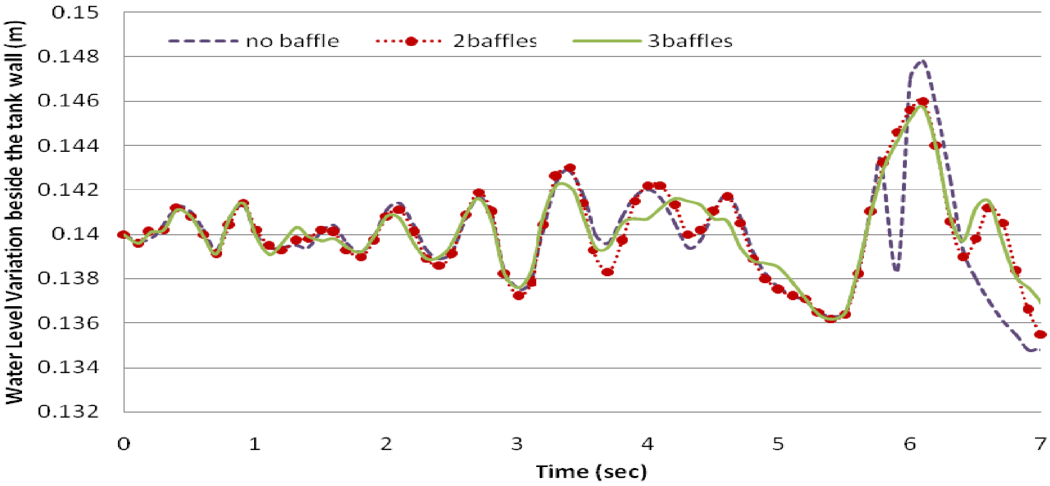

Figure 15: Water level variations beside the tank wall with different number of baffles, when subjected to the scaled Chi-Chi (Chy024) record

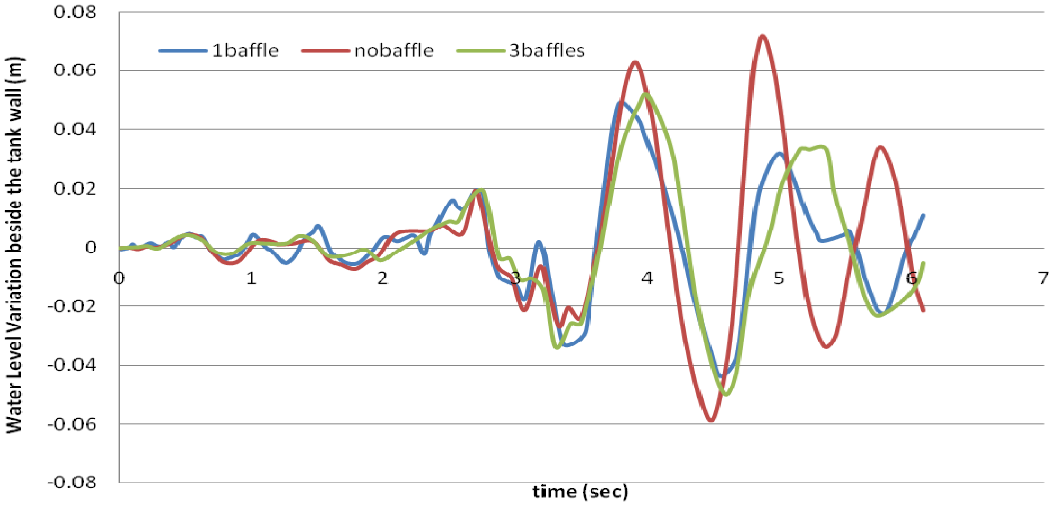

Figure 16: Water level variations beside the tank wall with different number of baffles, when subjected to the scaled San Fernando record

It is seen in Figures 14 to 16 that using baffles in general 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 Tabas, Iran (1987) and Kocaeli, Turkey (1999) showed that using more than 3, and in some cases 2, baffles does not change the results so much. Therefore, it can be recommended that 2 baffles are used in tanks of the sizes around the size of the studied tank.

6 NEURAL NETWORK AND ITS TRAINING FOR SLOSHING RESPONSE PREDICTION

To train a neural network for prediction of the sloshing response to earthquake excitations, the results of Kocaeli (1999), Tabas (1987), and Chi-Chi (Chy024 component -1999) earthquakes were used. The values of pseudo velocities corresponding to the 1st, 2nd, and 3rd sloshing modes in the tank, along with the number of baffles were used and the input data, and the ratio of water level increase to the water depth was used as the output data (Table 2).

Table 2: Input and output data used for training the considered neural network

	Name of Earthq.	X_1=Number of baffle(s)	X_2=Pseudo velocity	Water level increase (cm)	Y_1=Water level increase / Water depth
1	Kocaeli	0	0.3463	26	0.565217391
2			0.827	26	0.565217391
3			1.001	26	0.565217391
4		1	0.3463	26	0.565217391
5			0.827	26	0.565217391
6			1.001	26	0.565217391
7		2	0.3463	21	0.512195122
8			0.827	21	0.512195122
9			1.001	21	0.512195122
10		3	0.3463	21	0.512195122
11			0.827	21	0.512195122
12			1.001	21	0.512195122
13	Tabas	0	0.5658	7.5	0.272727273
14			0.8988	7.5	0.272727273
15			0.7549	7.5	0.272727273
16		1	0.5658	4.05	0.168399168
17			0.8988	4.05	0.168399168
18			0.7549	4.05	0.168399168
19		2	0.5658	3.6	0.152542373
20			0.8988	3.6	0.152542373
21			0.7549	3.6	0.152542373
22		3	0.5658	2.4	0.107142857
23			0.8988	2.4	0.107142857
24			0.7549	2.4	0.107142857
25	Chi-Chi (CHY024)	0	0.6337	60	0.75
26			0.7192	60	0.75
27			0.4451	60	0.75
28		1	0.6337	31.5	0.611650485
29			0.7192	31.5	0.611650485
30			0.4451	31.5	0.611650485
31		2	0.6337	36	0.642857143
32			0.7192	36	0.642857143
33			0.4451	36	0.642857143
34		3	0.6337	34.5	0.633027523
35			0.7192	34.5	0.633027523
36			0.4451	34.5	0.633027523

Based on the data given in Table 2, and by considering a neural network with one intermediate or hidden layer [8] (Figure 17), the network was trained. After training the neural network, to test its capability in response prediction, another earthquake (Chi-Chi, Chy101 component) was considered, whose displacement record is shown in Figure 17.

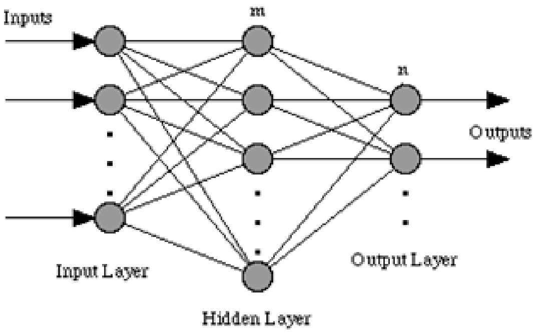

Figure 17: the neural network with one intermediate (hidden) layer [8]

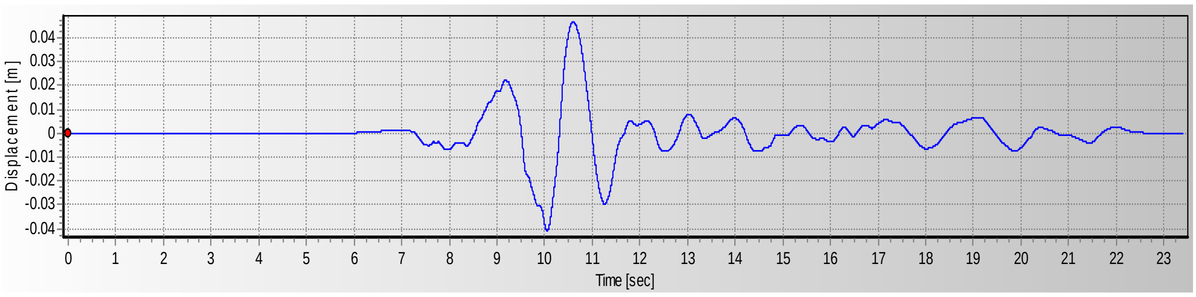

Figure 17: Displacement time history of Chi-Chi earthquake (CHY101 component)

The results, obtained by FE element analysis of the sloshing response of the tank, subjected to the test record are given in Table 3.

Table 3: Input and output data obtained from the test record for checking the trained neural network

	Name of Earthq.	X_1=Number of baffle(s)	X_2=Pseudo velocity	Water level increase (cm)	Y1=Water level increase / Water depth
1	Chi-Chi (CHY101)	0	0.5358	33*	0.622641509
2			0.4025	33	0.622641509
3			0.3115	33	0.622641509
4		1	0.5358	27	0.574468085
5			0.4025	27	0.574468085
6			0.3115	27	0.574468085
7		2	0.5358	18	0.473684211
8			0.4025	18	0.473684211
9			0.3115	18	0.473684211
10		3	0.5358	18	0.473684211
11			0.4025	18	0.473684211
12			0.3115	18	0.473684211

* Results are related to the tank with actual size.

Figure 18 shows the results obtained by the trained neural network in comparison with those obtained by the time history analysis of the numerical FE model.

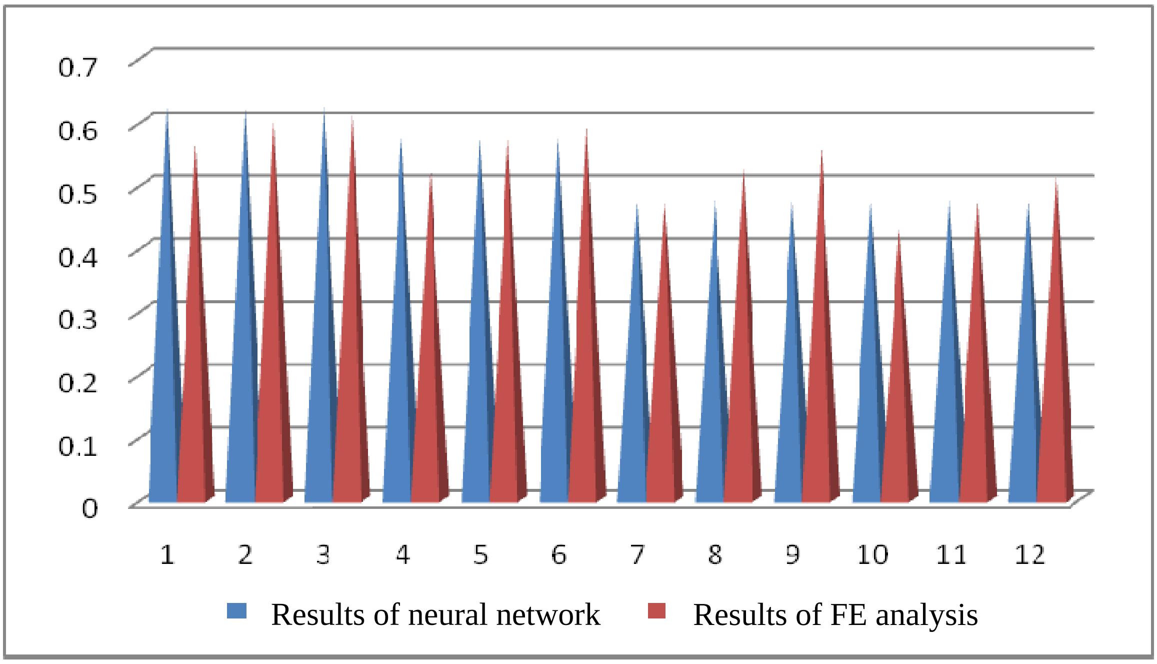

Figure 18: The results of the trained neural network in comparison with those of the FE analysis

It can be seen in Figure 18 that the trained neural network can predict the sloshing response with satisfactory precision.

7 CONCLUSIONS

Based on the numerical finite element analysis of the tanks in this study and the proposed neural network response prediction method, 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 analysis required time.
- When the excitation is in one of the main directions of the rectangular tank, the width of tank can be chosen as small as 10 cm. This also will lead to reduction of the analysis required time.
- Using 2 to 4 vertical baffles, equally spaced along the rectangular tanks, can reduce the sloshing effect to a great extent.
- The proposed neural network can be used for predicting the sloshing response in tanks with satisfactory precision, and therefore, it is recommended that this approach is used for studying the sloshing problem in tanks instead of time history analysis, which is very time consuming.

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