EVALUATING THE EFFECT OF MULTIPLE VERTICAL ORTHOGONAL BAFFLES ON SLOSHING PHENOMENON IN RECTANGULAR TANKS SUBJECTED TO 3-DIMENSIONAL EARTHQUAKE EXCITATIONS

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ABSTRACT

One of the most important phenomena in liquid storage tanks, subjected to earthquake excitations, is sloshing which can cause severe damages, particularly to tank's roofs. Recent studies on rectangular tanks have proven that using multiple vertical baffles can reduce the sloshing effect to a great extent. However, in those studies baffles have been considered to be just in one direction perpendicular to the propagation direction of the main sloshing wave. In this study the effect of using Multiple Vertical Orthogonal Baffles (MVOB), consisting of one and two baffle(s) in each main direction, parallel to the tank side, has been investigated. For this purpose several cases of Time History Analysis (THA), using three-component accelerograms of a set of selected earthquakes have been used. For investigating the dynamic behavior of impounded water the Volume of Fluid (VOF) method has been employed, which uses an advection algorithm for the volume of fraction, varying from zero to one for each element. Precision of the numerical modeling and VOF analyses has been verified by some experimental results from an independent previous study. For numerical analyses some far-source earthquake records which can intensely excite the sloshing phenomenon have been considered. Numerical results obtained by THA show that using just two pairs of MVOB can reduce the maximum water level around 40% for most earthquakes. The effects of vertical ground acceleration in the variation of sloshing as well as hydro-dynamic pressure also have investigated, and it can be said that the vertical component of ground motion does not have much effect on sloshing height, while its affects hydro-dynamic pressure to some extent, leading to increase in the shear forces and bending moments in walls up to 40%.

Keywords: Multiple Vertical Orthogonal Baffles (MVOB), Time history analysis (THA), Volume of Fluid (VOF) method, Sloshing, Hydro-Dynamic pressure

1. INTRODUCTION

Liquid sloshing which occurs in a partially filled tank subjected an external excitation is a known

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physical phenomenon, and it will cause destructive damage due to the earthquake. Reducing the effects of earthquake induced sloshing is one of the important priorities for earthquake engineers. To decrease damage and economic losses in liquid storage tanks, use of baffles are suggested. Choun (1996, 1999) used a linear theory to investigate the effects of the size and location of submerged block to reduce the sloshing of the fluid. Isaacson and Premasiri (2001) developed a hydrodynamic model to investigate the effectiveness of baffles to increase the hydrodynamic damping in a rectangular tank. Goudarzi and his colleagues (2010) estimated the hydrodynamic damping ratio of liquid sloshing for wall bounded baffles, using the velocity potential formulation and linear theory. They observed that hydrodynamic damping is significantly affected by the size and location of baffles.

There are different numerical methods to investigate sloshing problems. Volume of fluid (VOF) technique with arbitrary-Lagrangian-Eulerian formulation is one of the general numerical simulations which is carried out to investigate sloshing waves (Eswaran et al. 2009). They studied the response of the coupled system, including baffled and un-baffled tanks, with VOF method in a 2-D state. It is obvious that 3-D analyses are more complicated and time-consuming than 2-D analyses. Liu and Lin (2009) investigated the concept of virtual boundary force method to model the internal baffles in 3-D state. Their results show that, for small amplitude sloshing, the numerical results agree very well with linear theory, while for large amplitude sloshing the numerical results deviate from the linear analytical solution. The other 3-D analysis has been conducted by Jung and colleagues (2012).

In this study, the effect of using multiple vertical orthogonal baffles (MVOB), in rectangular tanks subjected to 3-D earthquake excitations, is investigated by Volume of Fluid (VOF) method to see if using these baffles can diminish the sloshing height and reduce the hydro-dynamic pressure, and also to see if the vertical component of earthquake has any effect on sloshing height and the hydro-dynamic pressure. Details of the study are presented in the following sections.

2. GOVERNING EQUATIONS

In order to solve the equation related to free surface flow as multiphase situation where the fluids are separated by distinct resolvable interface, the VOF, Eulerian-Eulerian homogeneous model is used, that is, the volume fractions of the phases are equal to one or zero everywhere except at the phase boundaries. In this study, the element based finite volume method package, ANSYS CFX, is used to solve Navier- Stokes equations. The homogenous hydrodynamic equations include momentum, continuity, respectively, are as bellow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho U_i\right) + \frac{\partial}{\partial x_j}\left(\rho U_j U_i\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_{eff}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right. \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \emptyset) + \frac{\partial}{\partial x_j}(\rho U_j \emptyset) = \frac{\partial}{\partial x_j}\left(\Gamma_{eff}\left(\frac{\partial \emptyset}{\partial x_j}\right)\right) + S_{\emptyset} \quad (3)$$

where $\boldsymbol{\mu_{eff}}$ is effective velocity, $\boldsymbol{\rho}$ is the density, $\mathbf{U_i}$ **and** $\mathbf{U_j}$ are the velocity of phases α and β, and $\boldsymbol{\Gamma_{eff}}$ is diffusivity, and finally ∅ is a general scalar variable

3. NUMERICAL IMPLEMENTATION

In this section, the procedure of numerical modeling is briefly explained. The details of verification numerical model can be found in a previous study by the authors of this paper (Hosseini and Farshadmanesh, 2011). A sample of the numerical model of the tank is shown in Figure 1.

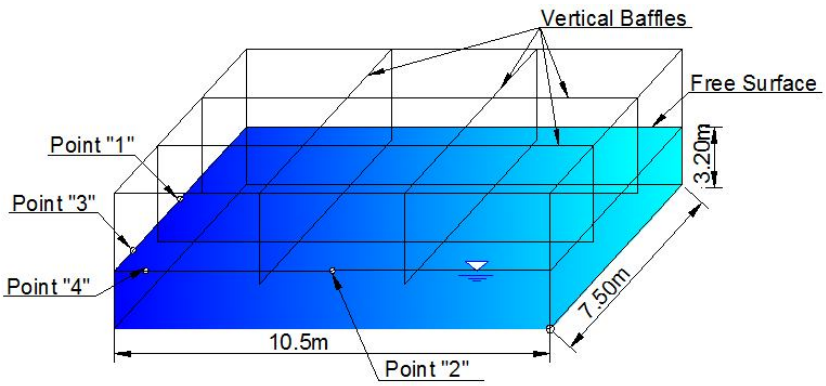

Figure 1: Rectangular tank with MVOB

In Figure 1 the points chosen for investigating the response values including sloshing height, are also shown. Liquid is considered incompressible and inviscid. In order to reduce the effects of sloshing, MVOB are assumed to be connected to the ceiling of the tank, and they are equally spaced. The bottom level of MVOB is considered to be the level of the convective mass based on Housner formulation (1954). The computational parameters are selected based on the sensitivity study by Godderidge and his colleagues (2006).

Regarding that the most severe sloshing occurs when the dominant frequency of earthquake excitation and the fundamental natural frequency of sloshing coincide, in order to excite the fundamental sloshing mode, it is necessary to select some appropriate long period earthquakes records. For this purpose equation (4) is used to obtain the fundamental frequency of the tank.

$$\omega_n^2 = (2n-1)\frac{\pi g}{L}\tanh\left((2n-1)\frac{\pi H_w}{L}\right) \quad (4)$$

In equation (4) ω_n is the natural frequency corresponding to the nth sloshing mode, and g is gravitational constant, L is the tank length in the direction of sloshing occurrence, and H_w is the water depth in the tank. Considering the dimensions given in Figure 1 the sloshing periods of the tank in its short and long main directions are obtained respectively 3.319 and 4.254 seconds. On this basis, the earthquakes shown in Table 1 have been selected.

Table 1: The selected earthquake with long period for exciting the sloshing modes of the tank

Selected earthquakes	Earthquake magnitude	Epicentral Distance (km)	PGA (g)	PGD (cm)
Imperial Valley, 1979	6.53	27.64	0.420	40.83
Northridge, 1994	6.69	13.39	0.459	12.06
Chi-Chi, Taiwan, 1999	7.62	31.96	0.382	53.62
Kocaeli, Turkey, 1999	7.51	19.30	0.306	54.70
Manjil, Iran, 1990	7.37	40.43	0.505	18.96

All of the selected earthquakes have relatively high energy in the range of long periods, and therefore, are quite appropriate for studying the sloshing effect.

4. NUMERICAL RESULTS

To investigate the positive effects of MVOB, the sloshing height in some specific points of the tank, shown in Figure 1, which are more critical locations, have been considered. With regard to baffles, three cases have been considered, including no baffle, one baffle in each direction, and two baffles in each direction. The responses used for investigating the effect of using MVOB in reducing the sloshing include the time histories of water level variation at the four considered points beside the tank wall, as well as the time histories of hydrodynamic pressure at the corner of the tank bottom. To see the effect of baffles in reducing the sloshing height the water level variations at points 1 to 4 in case of Imperial Valley earthquake are shown in Figures 2 to 5. More results of this type for other earthquakes cannot be shown here because of lack of space, and can found in another work of the authors (Hosseini et al. 2013).

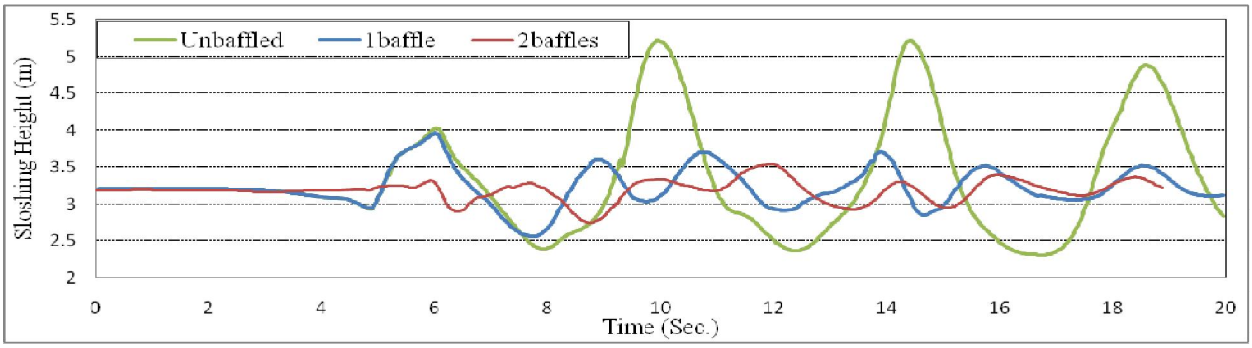

Figure 2: Water level variation at point 1, due to sloshing, subjected to Imperial Valley record

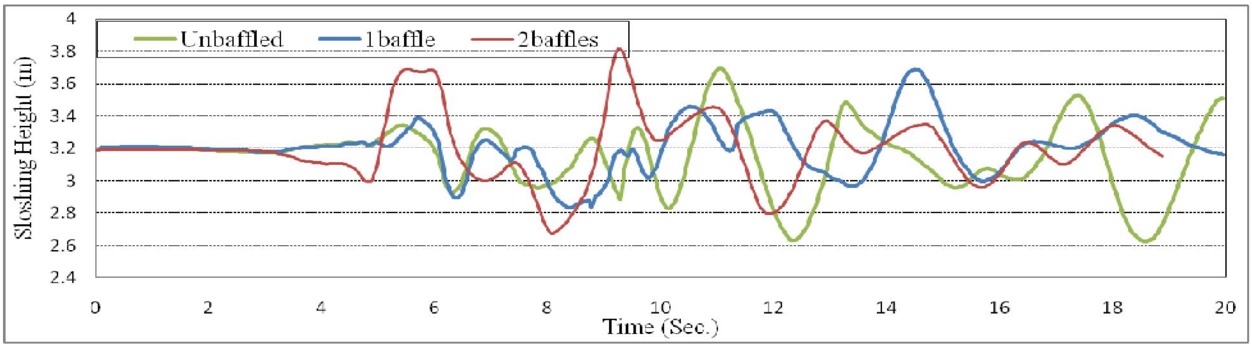

Figure 3: Water level variation at point 2, due to sloshing, subjected to Imperial Valley record

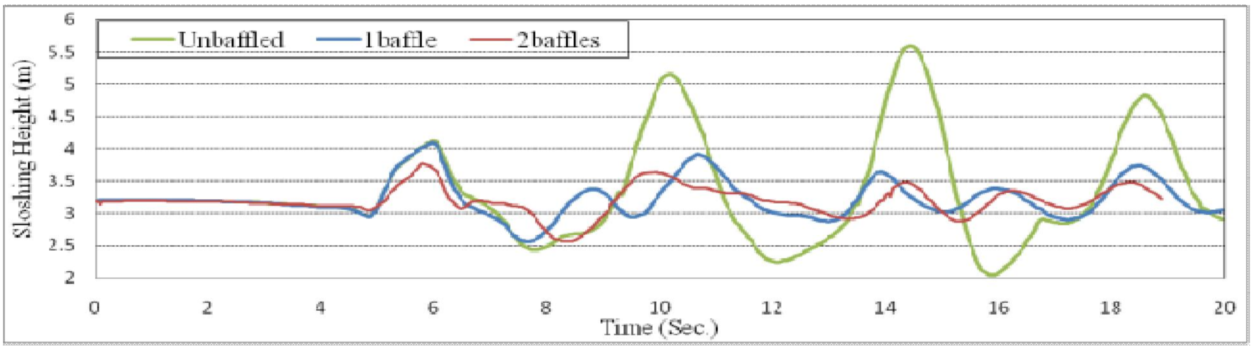

Figure 4: Water level variation at point 3, due to sloshing, subjected to Imperial Valley record

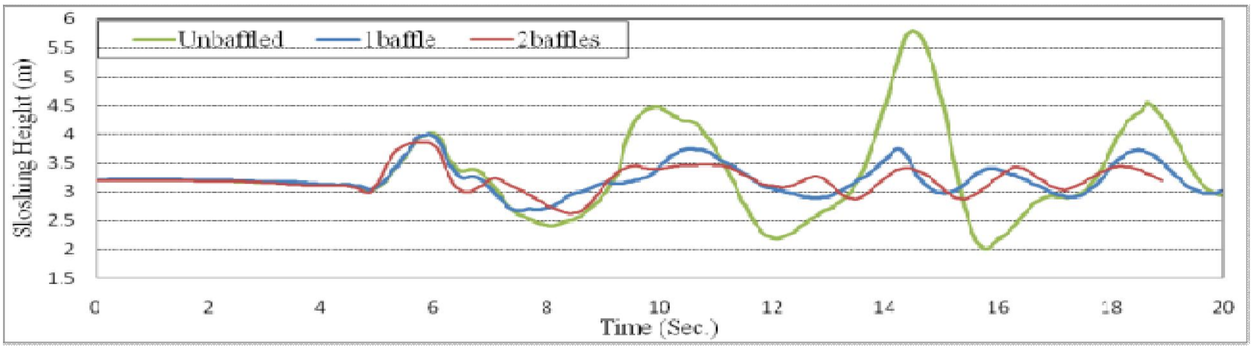

Figure 5: Water level variation at point 4, due to sloshing, subjected to Imperial Valley record

As it can be seen in Figures 2 to 5 the use of MVOB is usually quite effective in reducing the sloshing height in the critical locations of the tank. It is also notable that, as Figure 3 shows, at point 2 the use of baffles has a slightly negative effect, and increases the maximum sloshing height from 3.7 m to 3.8 m, however, considering the maximum sloshing height which is around 5.8 m, at point 4, as shown in Figure 5, this slight increase is not remarkable.

Another important response value for investigating the effect of MVOB is the hydrodynamic pressure. Figures 6 to 10 show the variations of hydrodynamic pressure at a corner point of the tank bottom, for all of the used earthquake records.

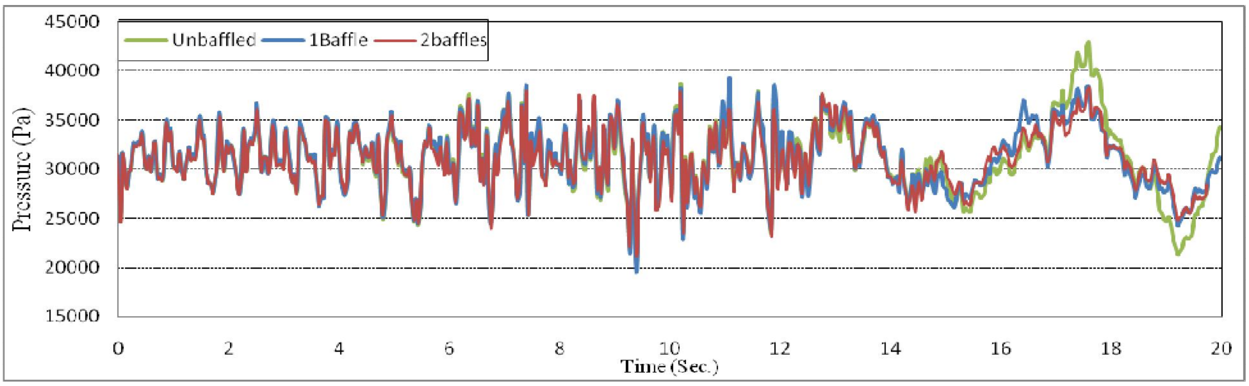

Figure 6: Variations of hydrodynamic pressure at the tank bottom subjected to Chi-Chi record

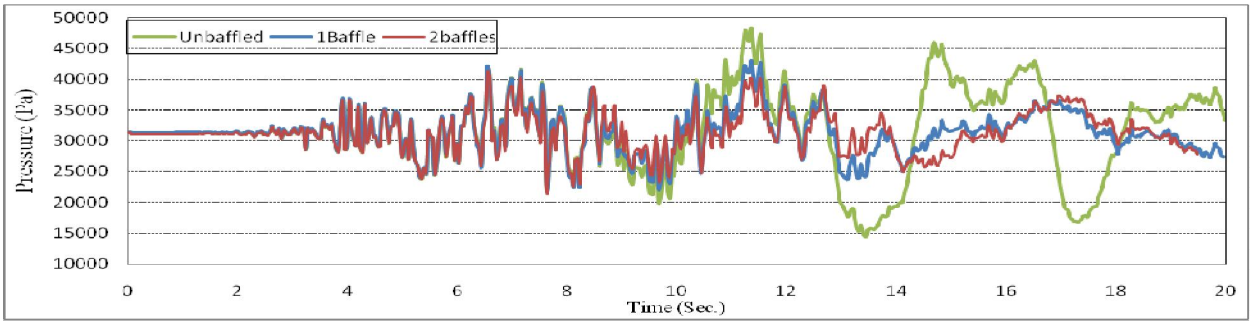

Figure 7: Variations of hydrodynamic pressure at the tank bottom subjected to Kocaeli record

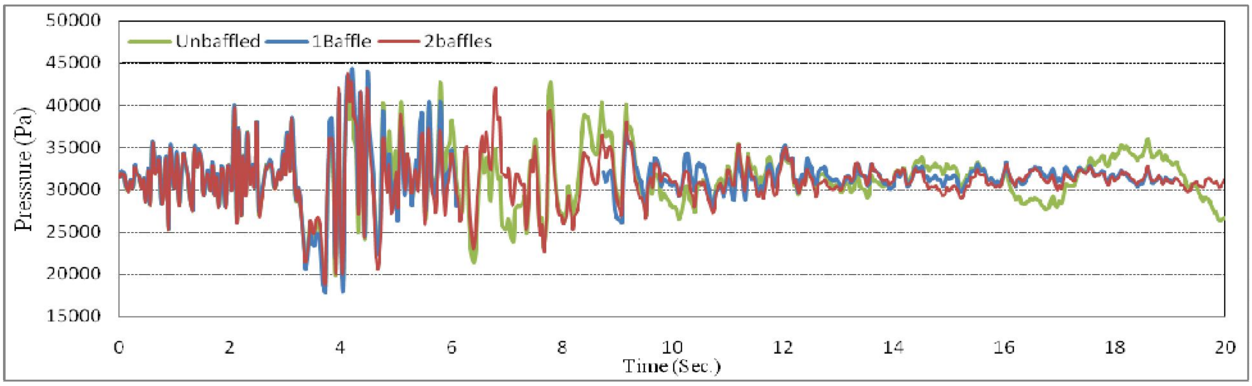

Figure 8: Variations of hydrodynamic pressure at the tank bottom subjected to Northridge record

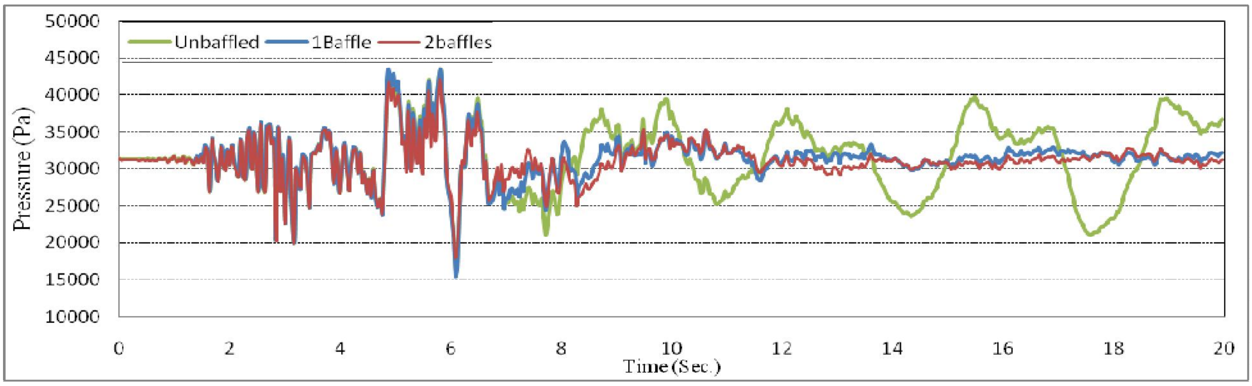

Figure 9: Variations of hydrodynamic pressure at the tank bottom subjected to Imperial Valley record

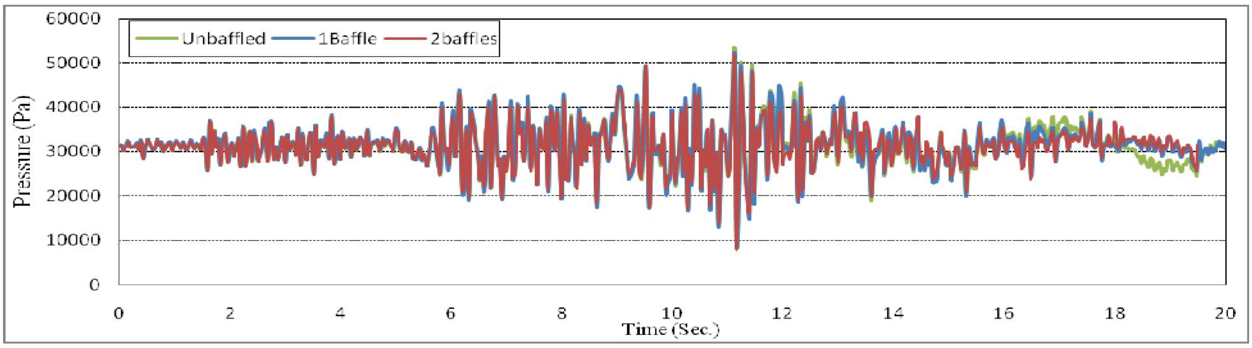

Figure 10: Variations of hydrodynamic pressure at the tank bottom subjected to Manjil record

It can be seen in Figures 6 to 10 that in most cases the use of MVOB has a decreasing effect on the hydrodynamic pressure at the tank bottom, however, this reduction is not as much as the reduction in sloshing height.

As the last set of numerical results, Figures 11 to 13 show the effect of vertical component of ground motion on the sloshing height as well as on the hydrodynamic pressure at the tank bottom.

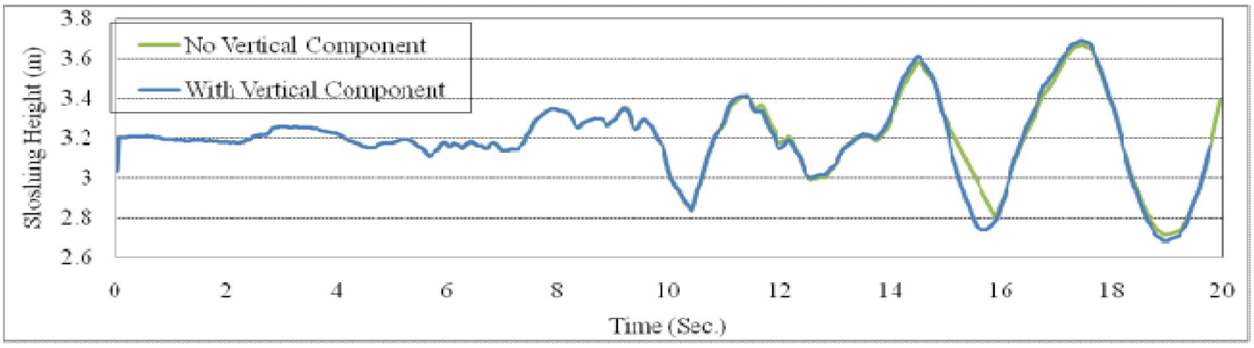

Figure 11: Sloshing height on the point 1 subjected to Manjil record

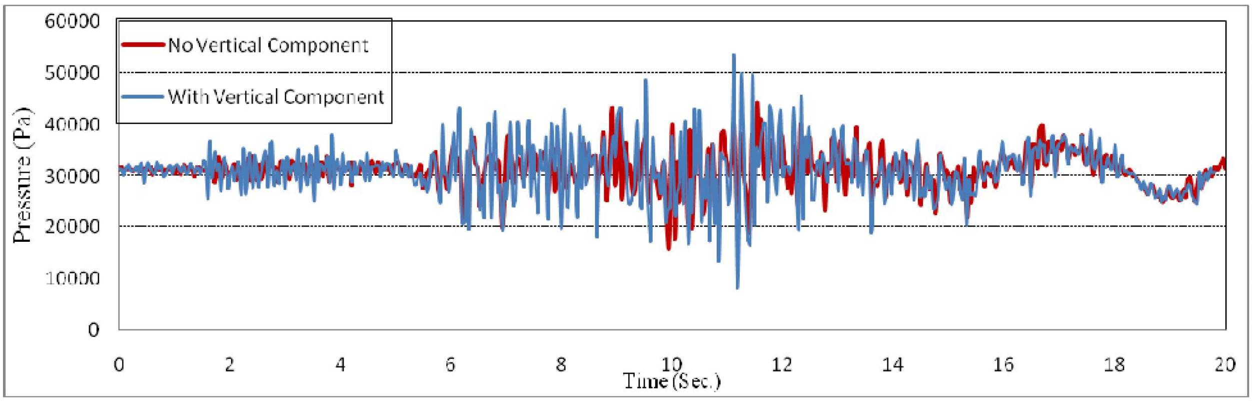

Figure 12: Hydrodynamic pressure on the tank bottom subjected to Manjil record

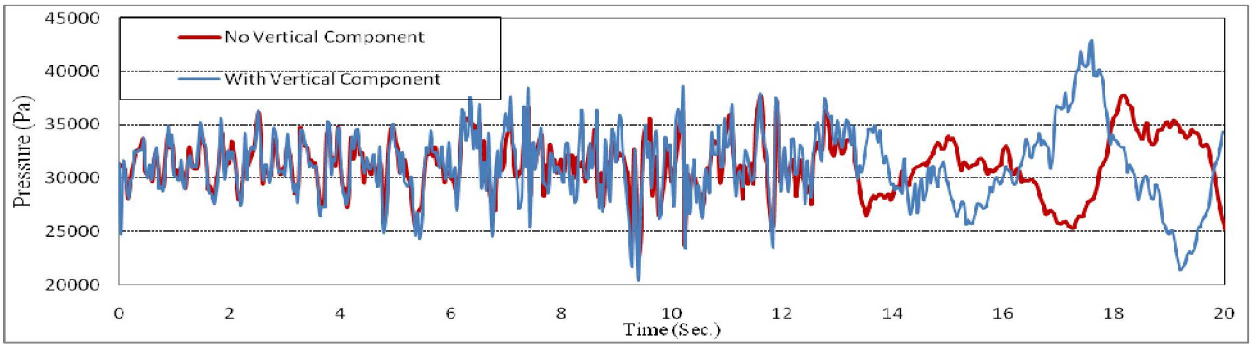

Figure 13: Hydrodynamic pressure on the tank bottom subjected to Chi-Chi record

As it is seen in Figure 11 the vertical ground motion does not have any significant effect on the sloshing height in the tank. However, as Figures 12 and 13 show the vertical ground excitation have increasing effect on the hydrodynamic pressure in the tank, which means that this effect should be considered in the design of tanks, particularly in near-source areas, where the vertical ground component has usually extensive acceleration values. Furthermore, comparing Figures 12 and 13, it can be seen that the effect of vertical ground motion is dependent on the type of earthquake.

5. CONCLUSIONS

Based on the numerical results obtained by THA it can be concluded that:

- Using just two pairs of MVOB can reduce the maximum water level around 40% for most earthquakes.
- The effects of vertical ground acceleration in variation of sloshing as well as hydro-dynamic pressure also have investigated, and it can be said that the vertical component of ground motion does not have much effect on sloshing height, while its affects hydro-dynamic pressure to some extent, leading to increase in the shear forces and bending moments in walls up to 40%.

Based on these results the use of MVOB can be recommended for new, and even existing tanks, to reduce their seismic sloshing response. It can be also recommended that the effect of vertical ground motion is taken into account for design of tanks, particularly in the near-fault areas; however, to reach reliable design provisions more research works are still required.

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