Numerical and Experimental Investigation of Rectangular Liquid Containing Structures under Seismic Excitation

Iman Bahreini Toussi [1], Majid Mohammadian [2], Risto Protic [3]

[1] Graduate research assistant, Department of Civil Engineering, University of Ottawa - Ottawa, ON, Canada.
[2] Professor, Department of Civil Engineering, University of Ottawa - Ottawa, ON, Canada.
[3] Structural Group Manager, Associated Engineering Alberta Ltd., Calgary, AB, Canada.

ABSTRACT:

Liquid Storage Tanks are mostly used for storing water, petroleum, industrial materials, etc. In seismic regions, it is important for these structures to remain functional after an earthquake. In this study, liquid behavior under base excitation is investigated by experiment as well as numerical modelling. For the experimental study, a shaking table is used to apply horizontal base excitation to a ground-supported rectangular tank. The tests are videotaped by high-speed HD video cameras in two directions and subsequently the videos are analyzed frame-by-frame. To find out the effect of bi-lateral excitation, the tank is placed on the shaking table on three different orientations. For the numerical modelling, the same tank size is simulated in OpenFOAM - a Computational Fluid Dynamics (CFD) program - and excitations same as the ones in the experiments are applied to the tank. The numerical results are compared with the ones from the experiments and the reliability of the numerical model is discussed.

Keywords: Seismic excitation, Liquid Storage Tanks, Numerical modelling, CFD, OpenFOAM.

INTRODUCTION

Liquid-Containing Structures are widely used for storage of various liquid types in municipalities, oil industry, food production, chemical plants, etc. Poor seismic performance of these structures in the past earthquake events has caused structural damages, economic losses and severe environmental problems. 1992 Landers earthquake that caused structural failure of tanks [1], 1960 Chilean earthquake that resulted in major damages to water reservoirs [2] and 1964 Niigata [3] and 2011 Tokohu [4] earthquakes in Japan after which uncontrollable fires in petroleum tanks occurred are some of the examples. An average of 200 earthquakes with magnitude of 6 Richter or more strike around the world each year [5], hence, the seismic design of Liquid-Containing Structures plays a crucial role in their design process. Also, it is important to keep water reservoirs functional during and after an earthquake since they have a crucial role in supplying drinking water to people suffering from the event and in extinguishing fires that are caused as a result of the earthquake. While a completely full or empty tank can be treated as a single mass system, partially filled tanks have a different story [6]. Liquid sloshing in a partially filled tank can cause large sloshing heights in open top tanks and large impact forces at the roof of closed tanks.

Numerous analytical, numerical and experimental studies on liquid storage tanks have been carried out by several researchers during the past decades. The sloshing problem has been studied in different aspects, from fluid viscosity to linearity or nonlinearity effect to tank's walls flexibility [7]. Fluid-Structure interaction problems require inter-disciplinary knowledge in topics such as fluid mechanics and structural engineering. There have been efforts in proposing analytical solutions for the sloshing problem. In 1957, Housner [8] proposed an analytical solution that was improved in his 1963 model [6]. In Housner's model, impulsive and convective masses are calculated using analytical formulations. The impulsive mass has a rigid connection with the walls of the tank while the convective one is modeled as a spring-mass system connected to the walls. The model is applicable in both cylindrical and rectangular tanks with some modifications. Veletsos (1974) [9], argued the Housner's model applicability in flexible tanks, and proposed a model to investigate the impulsive forces in a flexible tank. however, he used Housner's model for convective mass as it is not affected by the flexibility of the tank's wall. In a more recent analytical study, Isaacson (2010) [10] proposed an analytical approach to estimate the liquid surface in a base excited tank and predict the impact loads based on that estimated liquid height.

Current guidelines for seismic design of liquid storage tanks such as ACI 350.3 (2006) [11] are based on Housner's method with some modifications. In this design code, the impulsive and convective pressures are determined and used for design. Although this analytical method is easy to follow and appropriately predicts the natural frequency of the liquid-tank system, some recent studies (e.g. [3], [10], [12]) debated the accuracy of this method in certain occasions. Due to difficulties in finding analytical solutions [13] and with the development of computational systems and laboratory equipment in the recent years, researchers are interested in numerical and experimental studies more than before. Moslemi et al. (2011) [14] evaluated seismic response of a water reservoir elevated on a reinforced concrete shaft using finite element method. The method was validated for circular cylindrical ground-supported tanks in a previous study by the same authors [15]. In their FE model, they accounted for damping of the liquid and considered impulsive and convective parts separately as an advantage in comparison with previous analytical methods. Mitra and Sinhamahapatra (2007) [16] studied the sloshing characteristics (e.g. displacement, frequencies, mode shapes) and the hydrodynamic pressure on the walls for rectangular liquid storage tanks. Due to assumption of small amplitude waves, their analysis was limited to linear problems. Kolukula and Chellapandi (2013) [17] used finite element method based on mixed Eulerian-Lagrangian scheme to examine sloshing response in 2D numerical models due to the different behaviors of free surface and interior nodes, which behave like Lagrangian and Eulerian particles respectively. Jaiswal et al. (2008) [18] studied the dynamic characteristics of non-uniform circular and rectangular liquid containing tanks by both experiments and numerical studies and found a very good agreement between the resonance period based on their numerical and experimental studies and the analytical solution based on Housner's model. Gui and Jiang (2014) [19] adopted 2D and 3D OpenFOAM [20] models to investigate the sloshing problem, free surface motions and hydrodynamic behavior of the liquid under resonant excitation using the two-phase viscous fluid flow model. They showed that calculating the loads based on 2D models may lead to underestimation for the tank corners. Li et al. (2012) [21] investigated the motion of sloshing liquid in a ship motion using the Finite Volume Method.

Panigrahy et al. (2009) [22] conducted a series of experiments to find the pressure and changes of the free surface in a square tank placed on a shaking table driven by a DC motor. Akyildiz and Ünal (2005) [23] studied the sloshing of the liquid as well as the pressure distributions at different points in a rectangular tank using pressure transducers. Eswaran et al. (2009) [24] calculated the pressure in a cubic tank using six pressure sensors on various heights on a wall of the tank. Their tank was excited by a simple shaking table that created sinusoidal displacements.

The current study focuses on rectangular, ground-supported liquid storage tanks. The behavior of rectangular tanks is investigated using both experimental and numerical studies. The experimental tests are conducted in the structural laboratory at the University of Ottawa using transparent water tanks placed on a shaking table. For the numerical study, the OpenFOAM is adopted as the simulation tool. In this study, the effect of tank orientation on liquid surface and pressure was a parameter of interest.

In this paper, the experimental and numerical studies will be explained first followed by a discussion on pressure distribution on the roof of the tank.

EXPERIMENTAL STUDY

In this study, various experimental tests are performed on a rectangular tank with plan dimensions of 755×300 mm and height of 300 mm. A uni-axial shaking table is used to apply base excitations to the tank. To investigate the bi-directional effect of excitation, the tank is placed on the shaking table in four different orientations of 0°, 30°, 60°, 90° as shown in Figure 1. The tank - made of plexiglass - was fully fixed to the base. Also, blue color was added to ease the observation of the water inside the tank. The experiment setup is shown in Figure 2. The tank is filled up to 1/3 and 2/3 of its height with coloured water on each orientation to observe the effect of orientation on changes of the liquid free surface and the associated pressure on the walls and roof of the tank.

The tests are recorded by two high-speed HD video cameras from two directions. Following the tests, the videos are analyzed frame-by-frame to investigate the liquid surface for each test case.

An actual earthquake using N-S Component of the 1940 El-Centro ground motion of which acceleration, velocity and displacement time histories are shown in Figure 3 with maximum values of 0.319g, 361.4 mm/s and (-213.4 : +28.6) mm respectively [25]. Also, harmonic sinusoidal base excitations are applied to the tank. Three harmonic base excitations with different frequencies were applied for a period of 60 seconds. The harmonic excitations include resonance condition and two other excitations within ±50% of the resonant frequency. The total movement domain of the sinusoidal excitations is chosen to be 10% of the tank's length (i.e. 70 mm), hence the displacement amplitude equals 5% of the length (i.e. 35mm). The resonance frequency is calculated based on formulations provided by Housner's model.

Any harmonic sinusoidal wave can be described by the following equation:

$$u(t) = A\, sin(\omega t) \qquad (1)$$

where u is the displacement (mm), A is the displacement amplitude (mm), ω is the excitation frequency (rad/s), and t is the time (s).

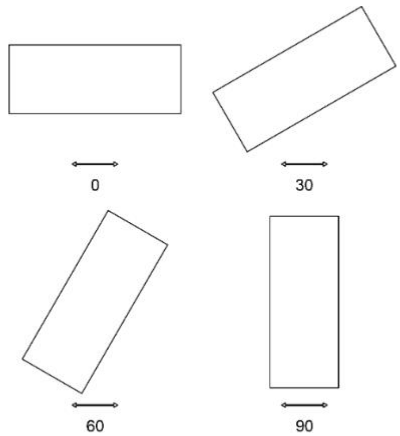

Figure 1-Excitation direction and tank orientations (plan view)

The calculated values for ω in each case are presented in Table 1.

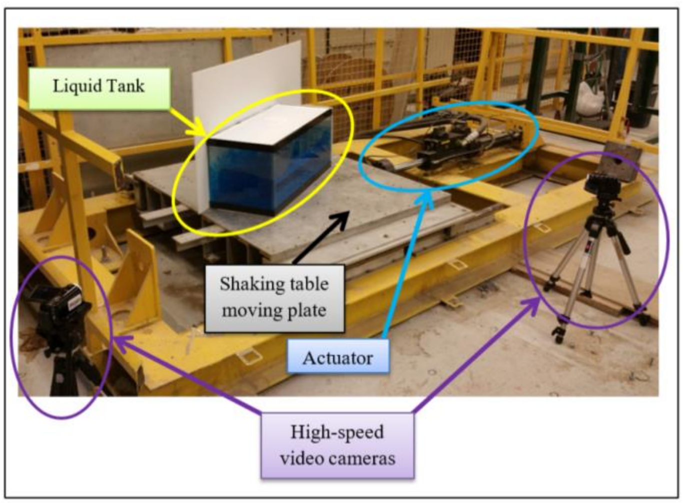

Figure 2- Experiment setup

The frames captured from each experimental test are compared with those of the same test simulated in OpenFOAM to validate the numerical model for further investigations. Results from the numerical model and experimental tests were compared for all the excitation types, frequencies and orientations.

Table 1- Applied frequencies for harmonic excitations

Case	Frequency (rad/s)	
100 mm liquid depth	Lower than resonance	2.02
	Resonance	4.03
	Higher than resonance	6.05
200 mm liquid depth	Lower than resonance	2.65
	Resonance	5.30
	Higher than resonance	7.95

It was observed from the experimental tests that the sloshing height amplified at the tank corners in comparison with other locations of the tank. This amplification occurred under both bi-lateral and uni-lateral excitations (Figure 4). This can lead to higher pressures at the corners compared to other tank locations. In a tank that is not aligned with the excitation direction (i.e. has a different orientation), the sloshing height at the sharp corners is even higher than that when a tank that is aligned with the excitation.

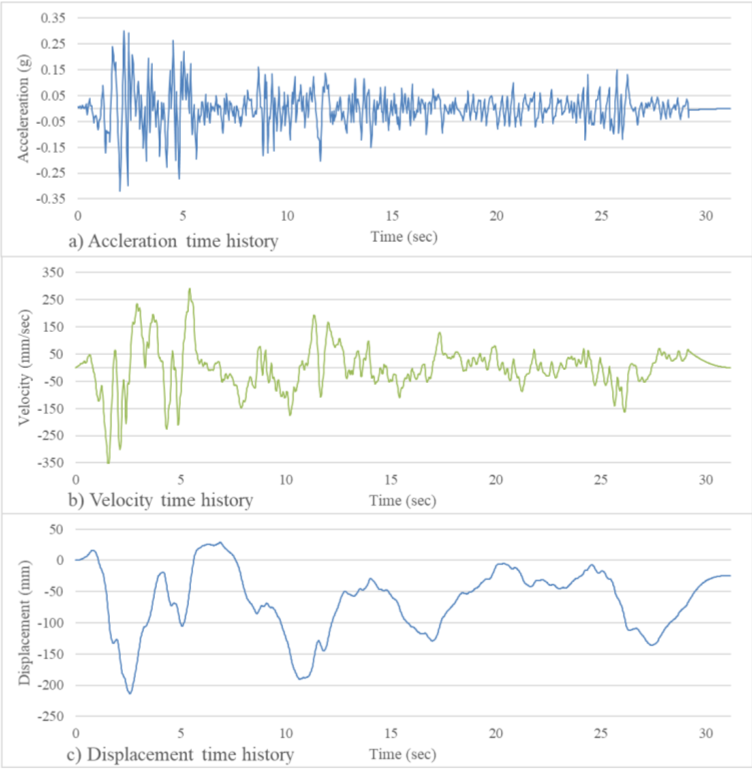

Figure 3- (a) Acceleration, (b) velocity and (c) displacement time histories for N-S Component of 1940 El-Centro ground motion

NUMERICAL MODELING

The numerical modelling software OpenFOAM was used for simulation of the tank and liquid behavior. It is an open source Computational Fluid Dynamics (CFD) software, capable of solving a large variety of problems, from dam break to heat transfer. Different CFD solvers are available in this application that can be used in the desired cases [26], [27]. The adopted numerical approach is Finite Volume Method (FVM), in which the Navier-Stokes equations (2 to 4) - which govern fluid dynamics problems - are numerically solved for each "control volume". Various turbulence models can be used in this software [28].

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\nabla^2 u \qquad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\nabla^2 v \qquad (3)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\nabla^2 w - g \qquad (4)$$

In these equations ρ is the liquid density (kg/m^3), p is total pressure (Pa), u, v and w are particle speeds in x, y and z directions respectively (m/s), t is time (s), $g = 9.81\ {}^{m}/{}_{s^2}$ (gravitational acceleration), ν is viscosity (m^2/s) and

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \qquad (5)$$

It should be noted that the Navier-Stokes equations are non-linear, hence OpenFOAM uses non-linear methods to solve them.

In the current study, the first step was to validate the model through the frames captured from the experimental tests and comparing them with the ones from the numerical simulations as shown in Figure 5. Following validation, pressure sensors were placed at various locations on the roof of the tank in the numerical model and simulations were conducted to find the maximum liquid pressure on the tank roof under both harmonic and earthquake excitations.

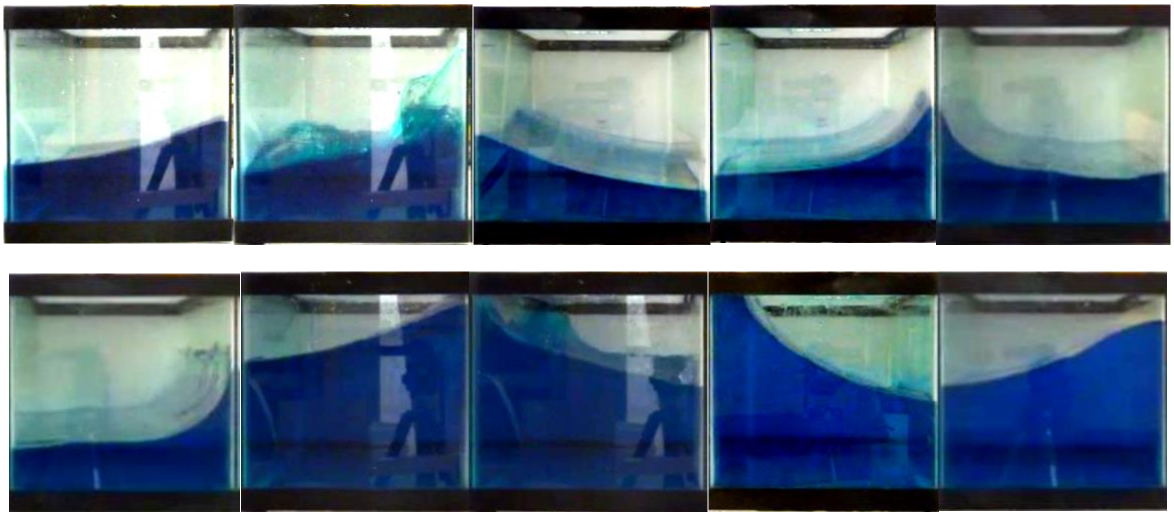

Figure 4- Higher liquid height observed near the corners of the tank in different orientations and excitation types

The OpenFOAM solver used in this study was interDyMFoam, which can solve problems with dynamic mesh. In this solver, pressure correction algorithm is used for the fluid flow and Volume of Fluid (VOF) method is adopted for tracking the free surface.

The Volume of Fluid VOF method, first introduced by Hirt and Nichols (1981) [28], is used in conjugation with other numerical methods to track the free surface. In this method, a function F is defined with the value of one for every spot that fluid exists and zero for other points. In each cell, the average value of F shows how much of that cell is filled with fluid. Hence, unit value of F means the cell is fully occupied by fluid and zero means there is no fluid in the cell. An F value between zero and one shows there is a free surface in that cell. Thus, the free surface can be tracked.

To validate the model, in addition to the qualitative comparison, the liquid surface was also digitized using MATLAB for a more detailed comparison in several cases. Figure 6 shows the digitized free surfaces of the liquid in some of the cases. In addition to the liquid surface at different time steps, the liquid height over time at the corner of the tank was measured in both numerical simulations and experimental tests for the earthquake excitations (Figure 7) and Fourier transform of the same parameter was compared for the two parts of the study. Despite the complex dynamical behavior of the system, maximum water elevation values are correctly predicted but the difference increases over time due to accumulation of errors. The comparison graphs (i.e. Figure 7) show that despite a delay at the beginning of the excitation (i.e. two seconds from the start time), the two graphs illustrate the same pattern and values for the rest of the time. Also, a common way of comparing signals is to apply Fourier transform to the two signals and compare them in Fourier space. It can be seen that the Fourier transform confirms that the numerical simulation’s spectrum is similar to the one from the experimental test.

CONCLUSION

In this study, a liquid tank with certain dimensions was tested experimentally on a shaking table and numerically using the OpenFOAM software. The purpose of this study was to develop a numerical model to simulate the response of liquid storage tanks under seismic excitations. Various base excitations including harmonic as well as an actual earthquake were applied to the tank base that was filled with water up to 1/3 and 2/3 of its height. Various excitations were applied in four different horizontal orientations to consider the effect of bi-directional motion.

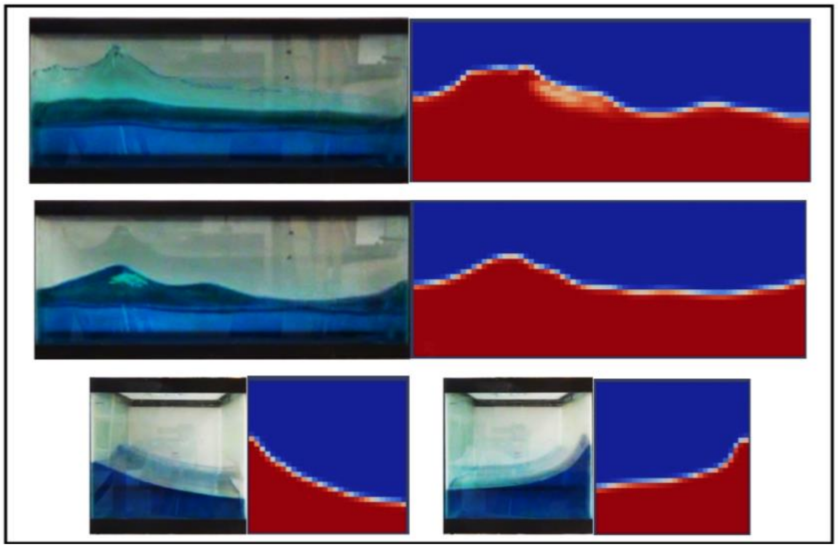

Figure 5- Qualitative comparison of liquid free surface in experimental (left) and numerical (right) studies in the tank with 100 mm of water, 60° orientation and frequency of higher than resonance

Observations from both the experimental tests and the numerical modellings showed that the Housner's simplified analytical model accurately predicts the natural frequency of the first mode of the liquid system. In other words, one can use Housner's simplified model to predict the frequency of the first mode of the liquid surface. In addition, it was found that regardless of excitation type and frequency and the tank orientation on the shaking table, the sloshing height at the corners of the tank is higher than the middle of the walls.

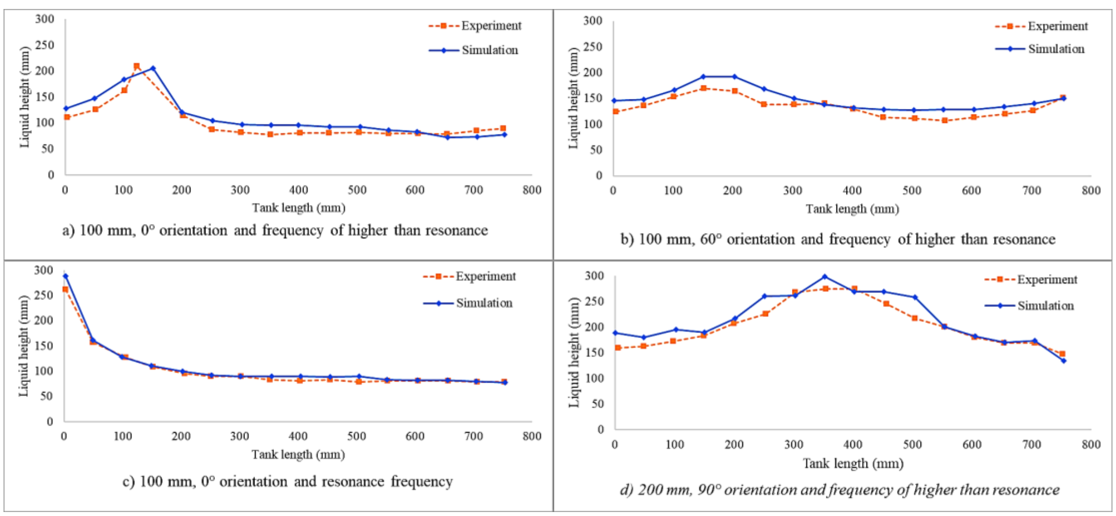

Figure 6- Comparison of free surface in numerical and experimental studies; (a) 100 mm water depth, 0° orientation, higher than resonance frequency, (b) 100 mm water depth, 60° orientation, higher than resonance frequency, (c) 100 mm water depth, 0° orientation, resonance frequency, (d) 200 mm water depth, 90° orientation, higher than resonance frequency

For model validation, harmonic excitations' videos were captured from the experiments, analyzed frame by frame and compared to the frames from the same cycle of the numerical simulations.

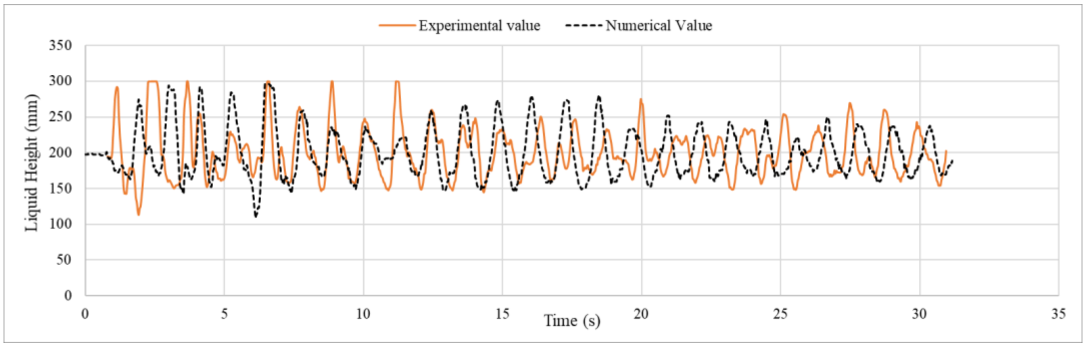

Figure 7- Comparison between the experimental and numerical values of water surface at the corner of the tank excited by El-Centro earthquake

Since an earthquake in terms of frequency and amplitude is a random phenomenon, to validate the model for the applied earthquake, in addition to the frame by frame comparison (i.e. same as harmonic excitations), time histories of the liquid height at one corner of the tank as well as the Fourier transform values of the liquid height were compared in the two parts of the study. Based on this evaluation, the validated model was used to estimate the applied pressures on the roof of the excited tank to determine the effect of such pressures at the corners of the tank in comparison with those at other roof locations near walls.

ACKNOWLEDGEMENT

This study was supported by research grants from Natural Sciences and Engineering Research Council of Canada (NSERC).

REFERENCES

[1] Cooper TW, Wachholz TP. Optimizing post-earthquake lifeline system reliability. In: Proceedings of the 5th US conference on lifeline earthquake engineering. ASCE, vol. 16. 1999, 878–86.

[2] Steinbrugge, K.V. and Flores, R., Engineering Report on the Chilean Earthquakes of May 1960 - A Structural Engineering Viewpoint, B.S.S.A., Vol. 53, NO. 2, 1963.

[3] Moslemi, M., Kianoush, M.R., Parametric study on dynamic behavior of cylindrical ground-supported tanks, Engineering Structures, Elsevier, 42 (2012) 214–230.

[4] Zama, S., Nishi, H., Hatayama, K., Yamada, M., Yoshihara, H., Ogawa, Y., On Damage of Oil Storage Tanks due to the 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0), Japan, Proceedings of the 15th world Conference on Earthquake Engineering, Lisboa, Portugal, 2012.

[5] Natural Resources Canada - NRCAN (http://www.earthquakescanada.nrcan.gc.ca/info-gen/magfreq-en.php)

[6] Housner, W.G., The Dynamic Behavior of Water Tanks, Bulletin of the Seismological Society of America, 53 (1963) 381-387.

[7] Wu, C.H., Chen, B.F., Transient Response of Sloshing Fluid in A Three-Dimensional Tank, Journal of Marine Science and Technology, Vol. 20, No. 1, pp. 26-37 (2012).

[8] Housner, W.G., Dynamic Pressures on Accelerated Fluid Containers, Bulletin of Seismological Society of America, 1957

[9] Veletsos, A.S., Seismic Effects in Flexible Liquid Storage Tanks, Proceedings of the 5th world conference on Earthquake Engineering, Vol. 1, 1974

[10] Isaacson, M., Earthquake-induced hydrodynamic forces on reservoir roofs, Can. J. Civ. Eng. 37: 1107–1115 (2010).

[11] ACI 350.3, Seismic Design of Liquid-Containing Concrete Structures and Commentary (ACI 350.3-6), American Concrete Institute, 2006.

[12] Ghaemmaghami, A. R., Kianoush, M. R., Effect of Wall Flexibility on Dynamic Response of Concrete Rectangular Liquid Storage Tanks under Horizontal and Vertical Ground Motions, J. Struct. Eng., Elsevier, 2010, 136(4): 441-451.

[13] Xiong, Y.P., Xing, J.T., Transient Dynamic Responses of An Integrated Air-Liquid-Elastic Tank Interaction System Subject to Earthquake Excitations, Proceedings of the 2008 ASME Pressure Vessels and Piping Division Conference, Chicago, IL, 2008.

[14] Moslemi, M., Kianoush, M.R., Pogorzelski, W., Seismic response of liquid-filled elevated tanks, Engineering Structures, Elsevier, 33 (2011) 2074–2084.

[15] Ghaemmaghami, A. R., Moslemi, M., Kianoush, M. R., Dynamic behavior of concrete liquid tanks under horizontal and vertical ground motions using finite element method, Proceedings of the 9th US national and 10th Canadian Conference on Earthquake Engineering, Toronto, ON, Canada, 2010

[16] Mitra, S., Sinhamahapatra, K.P., Slosh dynamics of liquid-filled containers with submerged components using pressure-based finite element method, Journal of Sound and Vibration, Elsevier, 304 (2007) 361–381.

[17] Kolukula, S.S., Chellapandi, P., Nonlinear Finite Element Analysis of Sloshing, Advances in Numerical Analysis, Volume 2013, Article ID 571528, 2013.

[18] Jaiswal, O. R., Kulkarni, S., Pathak, P., A Study on Sloshing Frequencies of Fluid-Tank System, The 14th World Conference on Earthquake Engineering, Beijing, China, 2008.

[19] Gui, F., Jiang, S., Numerical simulation of liquid sloshing problem under resonant excitation, J Advances in mechanical engineering, (2014) Article ID 834657.

[20] OpenFOAM version 2.3.1 [Computer software], OpenCFD Ltd., Bracknell, U.K.

[21] Li, Y., Zhu, R., Miao, G., Fan, J., Simulation of tank sloshing based on OpenFOAM and coupling with ship motions in time domain, Journal of Hydrodynamics, Elsevier, 2012, 24 (3): 450-457.

[22] Panigrahy, P.K., Saha, U.K., Maity, D., Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks, Ocean Engineering, Elsevier, 36 (2009) 213–222.

[23] Akyildiz, H., Ünal, E., Experimental investigation of pressure distribution on a rectangular tank due to the liquid sloshing, J Ocean Engineering, Elsevier, 32 (2005) 1503–1516.

[24] Eswaran, M., Saha, U.K., Maityb, D., Effect of baffles on a partially filled cubic tank: Numerical simulation and experimental validation, Journal of Computers and Structures, Elsevier, 87 (2009) 198–205.

[25] Chopra, A.K., Dynamics of structures: theory and applications to earthquake engineering, Prentice Hall Inc. 1995.

[26] Kheirkhah Gildeh, H., Numerical Modeling of Thermal/Saline Discharges in Coastal Waters, University of Ottawa, Department of Civil and Environmental Engineering, M. A. SC. Thesis, 2013.

[27] Barakati, A., Numerical modelling of liquid containing structure under dynamic loading, University of Ottawa, department of Civil and Environmental Engineering, M. A. Sc. Thesis, 2015.

[28] Hirt, C.W., Nichols, B.D., Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries, Journal of Computational Physics 39 (1981) 201-225.