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SLOSH DYNAMICS OF LIQUID FILLED BAFFLED TANK UNDER SEISMIC EXCITATIONS

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Seismic behavior of partially-filled rigid, rectangular liquid tank, with wall-mounted horizontal baffles, is numerically simulated using finite element method. A velocity potential based Galerkin-finite element model is developed for the numerical analysis. The dynamic behavior manifested in terms of sloshing elevation, base shear and overturning base moment are studied. The effect of position and dimension of the baffle on the above hydrodynamic parameters are investigated. It is observed that the baffle has significant influence on the free and forced vibration characteristics of the tank-liquid system. The sensitivity of the sloshing frequencies to the width of the baffle increases as the baffle position shifts towards the free surface of the liquid. For a given position of the baffle, the sloshing frequencies decrease with increase in the width of the baffle. It is concluded that decrease in sloshing elevation does not necessarily guarantee decrease in the hydrodynamic forces.

Keywords: sloshing, baffle, velocity potential, hydrodynamic pressure, base shear, base element

1 Introduction

Liquid containers comprise a major portion of important lifeline structures and are widely used in water supply facilities, oil and gas industries, and nuclear power plants for storage of an array of liquids and industrial wastes of diverse forms. The dynamic behavior of these systems is seriously disturbed by the dynamics of free liquid surface. The dynamics of free liquid surface in turn depends on several factors such as: nature, amplitude and frequency of external excitations; liquid fill-depth; geometrical and material characteristics of liquid-tank system; and support conditions at tank boundaries. The failure of large tank due to seismic excitations has far reaching consequences than the instant economic value of the tank and its content and may have long term insinuations in terms of environmental peril and human health. In fact heavy damages have been reported due to strong earthquakes which include those of most recent ones such as 2010 Maule, 2010-11 Christchurch and 2011 Tohoku-Pacific earthquake. The dynamic response of fluid-structure system is very sensitive to the characteristics of ground motion and configuration of the system (Haroun [1983], Haroun and Tayel [1985]). Chen et al. [1996] proposed a 2D finite difference model to simulate non-linear seismic finite-amplitude liquid sloshing in rectangular tank. Choun and Yun [1999] used small amplitude wave theory in their analytical study on the seismic behaviour of tank-liquid-submerged block system under various ground motions. Hamdan [2000] examined the accuracy of design guidelines of various codes for the seismic response of cylindrical steel liquid storage tanks and commented on the inadequacy of provisions of design guide lines against many of the commonly occurred failure modes reported during past earthquakes. Virella et al [2008] conducted a study in rectangular tanks and concluded that nonlinearity of the surface wave does not have major influence on the natural frequencies and on the pressure distribution on the walls. The dynamic responses of cylindrical steel tanks in various conditions were investigated by Hernández-Barrios [2007], Bayraktar et al. [2010], Estekanchi and Alembagheri [2012].

Sloshing effects are reduced naturally due to inherent liquid viscosity though, in practice the effect of viscosity on damping factor and other dynamic characteristics such as slosh displacement and hydrodynamic pressure on the wall of the container is not very significant. Several slosh suppression devices e.g., annular rings, floating plates and mats, baffles, lids and surfactants etc. have been employed to reduce sloshing effects. The objective of use of passive sloshing damper is to dissipate the sloshing motion energy by breaking a main sloshing flow into several weaker sub-streams. To this end, a typical low frequency seismic motion of 1979 Imperial Valley-06 (Holtville Post office) available online at http://peer.berkeley.edu/nga is selected as lateral ground motion for the numerical simulation of tank-liquid system with wall-mounted horizontal baffle.

2 System Geometry and Mathematical Formulation

Cartesian coordinate system O-xz for the computational domain of the liquid is defined such that the origin is at the center of the still free surface with z-axis pointing vertically upward. The liquid in the tank is assumed to be ideal. The free surface kinematic and dynamic boundary conditions are linearized and are combined together. The governing equation of motion of liquid in terms of *velocity potential* $\varphi(x,z,t)$ and the free surface and the body surface boundary conditions are listed as follows.

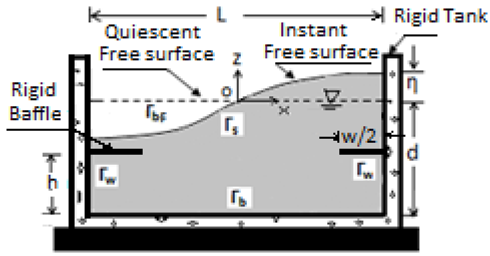

Figure 1. Schematic diagram of tank-baffle system

Governing equation:

$$\nabla^2\varphi = 0 \tag{1}$$

Free surface boundary condition:

$$\frac{\partial^2\varphi}{\partial t^2} + g\frac{\partial\varphi}{\partial z} = 0 \quad \text{on } \Gamma_s \tag{2}$$

Wall boundary condition:

$$\frac{\partial\varphi}{\partial n} = V_n \quad \text{on } \Gamma_w \tag{3}$$

Bottom boundary condition:

$$\frac{\partial\varphi}{\partial n} = 0 \quad \text{on } \Gamma_b \tag{4}$$

3 Finite Element Modelling

The liquid domain Ω bounded by $\Gamma = \Gamma_w \cup \Gamma_b \cup \Gamma_s$ is discretized by four-noded isoparametric quadrilateral element and velocity potential is considered as the nodal degree of freedom. The velocity potential is approximated as

$$\varphi \approx \varphi(x,z,t) = \sum_{j=1}^{n} \varphi_j N_j(x,z) \tag{5}$$

where φ_j are time dependent nodal vel ocity potentials, N_j are shape functions and n is the number of nodes. Application of Galerkin's weighted-residual method to Laplace equation gives rise to

$$\int_{\Omega} N_i \left(\nabla^2 \varphi\right) \mathrm{d}\,\Omega = 0 \qquad (6)$$

On application of divergence theorem, the above residual form reduces to

$$\int_{\Omega}\left[\frac{\partial N_i}{\partial x}\sum_{j=1}^{n}\frac{\partial N_j}{\partial x}\varphi_j + \frac{\partial N_i}{\partial z}\sum_{j=1}^{n}\frac{\partial N_j}{\partial z}\varphi_j\right] \mathrm{d}\,\Omega = \int_{\Gamma} N_i \frac{\partial \varphi}{\partial n}\mathrm{d}\,\Gamma \qquad (7)$$

Substituting boundary conditions of Equations (2)-(4) in the Eq. (7) we get

$$\int_{\Omega}\left[\frac{\partial N_i}{\partial x}\sum_{j=1}^{n}\frac{\partial N_j}{\partial x}\varphi_j + \frac{\partial N_i}{\partial z}\sum_{j=1}^{n}\frac{\partial N_j}{\partial z}\varphi_j\right]\mathrm{d}\,\Omega = \int_{\Gamma_w} N_i V_n d\,\Gamma_w - \frac{1}{g}\int_{\Gamma_s} N_i \sum_{j=1}^{n} N_j \ddot{\varphi}\,\mathrm{d}\,\Gamma_s \qquad (8)$$

$$\frac{1}{g}\int_{\Gamma_s} N_i \sum_{j=1}^{n} N_j \ddot{\varphi}\mathrm{d}\Gamma_s + \int_{\Omega}\left[\frac{\partial N_i}{\partial x}\sum_{j=1}^{n}\frac{\partial N_j}{\partial x}\varphi_j + \frac{\partial N_i}{\partial z}\sum_{j=1}^{n}\frac{\partial N_j}{\partial z}\varphi_j\right]\mathrm{d}\Omega = \int_{\Gamma w} N_\mathrm{i} V_n \mathrm{d}\Gamma_w \qquad (9)$$

Equation (9) may be expressed in matrix form as

$$[M_\mathrm{f}]\{\ddot{\phi}\} + [K_f]\{\phi\} = \{F\} \qquad (10)$$

Where $[M_f]$ is the free surface matrix; $[K_f]$ is the fluid coefficient matrix and $[F]$ is the force vector

The free slosh displacement η and hydrodynamic pressure p at any instant are obtained from the following equations.

$$\eta = -\frac{1}{g}\left(\frac{\partial \varphi}{\partial t}\right) \qquad (11)$$

$$p = -\rho\left(\frac{\partial \varphi}{\partial t}\right) \qquad (12)$$

The base shear S_b and overturning base moment can be calculated by the following expression

$$S_b = \int_{\Gamma_w} p\,\mathrm{d}\Gamma_w \qquad (13)$$

$$M_b = \int_{\Gamma_w} (p\,\mathrm{d}z) z + \int_{\Gamma_b} (p\,\mathrm{d}x) x \qquad (14)$$

4 Numerical results and Discussion

A finite element code in Matlab platform is developed for numerical simulation and investigation of the effect of wall-mounted baffle on free and force vibration responses of tank-liquid system under low frequency seismic motion of Imperial Valley as presented in Figure 2. The peak ground acceleration of the ground motion is scaled to a magnitude of 0.2g.

The governing parameters of the rectangular tank-liquid system are as follows:
L = 10 m; d = 5 m; density of liquid, ρ = 1000kg/m^3; and varied value of h

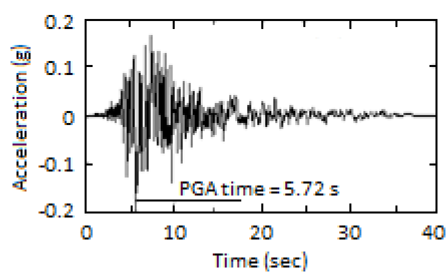

Figure 2. Ground motion of Imperial Valley

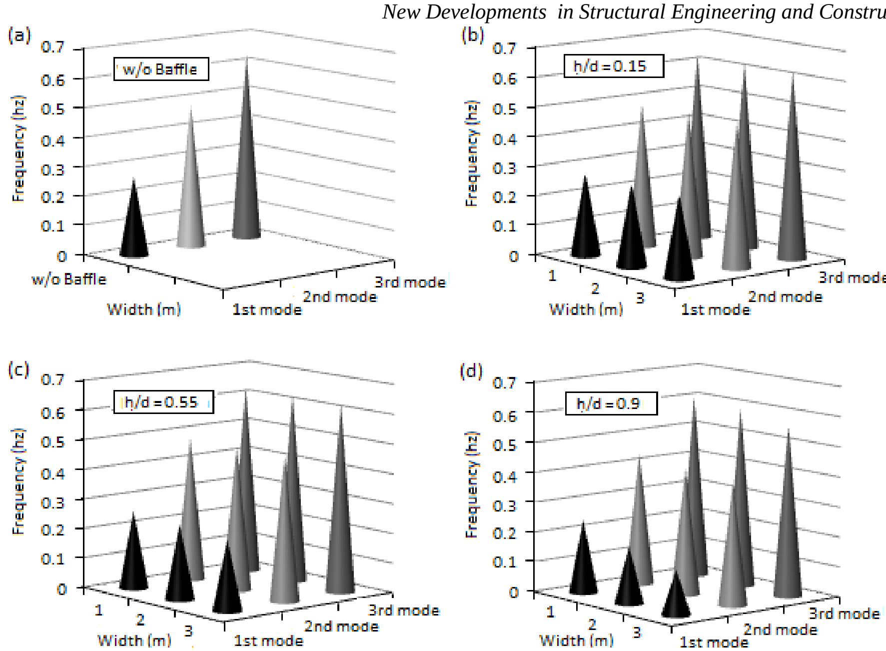

Figure 3. Variation of modal frequency with respect to the baffle width for different baffle position: (a) Without baffle, (b) $h/d = 0.15$, (c) $h/d = 0.55$, (d) $h/d = 0.9$

4.1 Free vibration analysis

Free vibration analysis is conducted by equating the value of external excitation in the right hand side of the finite element equation (10) as zero for eigenvalue solution. The results of first three antisymmetric modes of frequencies for different positions (heights) and dimensions (widths) of the baffle are shown in Figure 3.

The fundamental sloshing frequency of the liquid is the most sensitive to the baffle position and dimension. For a given position of the baffle, the sloshing frequencies decrease with increase in the width of the baffle. The sensitivity of the sloshing frequencies for a fixed width of the baffle increases as the baffle position shifts towards the free surface of the liquid. As the sloshing becomes violent when the excitation frequency becomes equal to or close to the fundamental frequency, the sloshing in a partially filled tank can be minimized by optimizing the baffle location and dimension. For baffle position, $h/d < 0.15$, higher frequency modes are almost insensitive to the baffle width. Hence, it may be concluded that baffles close to the tank bottom would not have any significant effect on the sloshing response of the liquid.

4.2 *Sloshing response*

One of the primary requirements of a safe design is the precise estimation of the required freeboard. Besides, pressures due to fluid impact during sloshing contribute to the overturning moment and thus may boost the possibility of uplift and buckling. Hence sensitiveness of sloshing response to the position and dimension of the baffle

Table 1. Hydrodynamic responses of various tank-baffle systems

Dimension of baffle		Hydrodynamic response components			
Position (*h/d*)	Width (*w/L*)	Sloshing (cm)		Base shear (kN/m)	Base moment (kN.m/m)
		+ve	-ve		
without baffle(wb)	without baffle(wb)	59.86	60.14	60.0	250.0
0.15	0.2	59.88	60.22	60.88	252.10
	0.4	59.75	60.31	61.70	257.16
	0.6	59.28	60.26	62.53	264.18
0.55	0.2	58.80	60.0	61.45	255.07
	0.4	65.75	67.17	62.41	258.74
	0.6	66.18	68.84	61.44	254.74
0.90	0.2	82.08	80.05	62.34	259.46
	0.4	50.61	43.74	69.83	281.28
	0.6	21.41	21.84	82.26	325.64

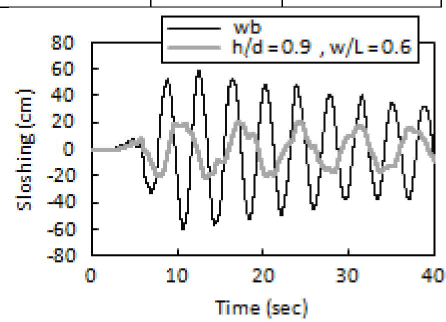

Figure 4. Comparison of time-history of slosh amplitude in tank with and without baffle

is studied. As the sloshing elevation and the free surface profile of liquid at a given instant represents the overall dynamic behaviour of liquid in its globality, their evolution over time in terms of time history of sloshing elevation at left wall free surface is studied and maximums of both positive and negative slosh displacements for various baffle positions and dimensions as recorded are presented in Table 1. One can observe from Figure 4. that for the tank in question, significant slosh reduction is achieved for the baffle location, h/d = 0.9, and width w/L = 0.6.

4.3 *Base shear and base moment*

A precise estimation of the base shear and overturning moment is important for judging the safety of tanks against shell buckling and uplift. The time-history analysis of base shear and base moment, due to the selected ground motion, for various cases of tank-baffle systems are computed and the absolute maximum values obtained from the time history plots are presented in

Table 1. Figure 5 and Figure 6 present the comparative results of base shear and base moment respectively for tank without baffle and a case with a given baffle position and dimension respectively.

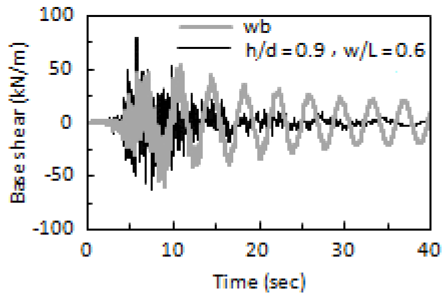

Figure 5. Comparison of time-history of hydro-dynamic base shear in tank with and without baffle

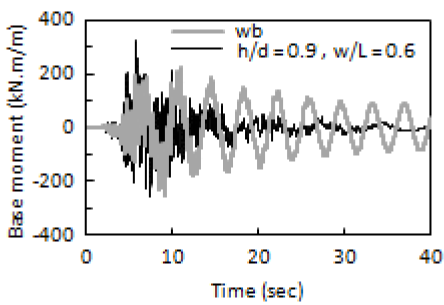

Figure 6. Comparison of time-history of hydrodynamic overturning base shear in tank with and without baffle

5 Conclusion

The effect of wall mounted baffle on the free vibration characteristics and the seismic response of partially filled rectangular tank is studied. The fundamental sloshing frequency of the liquid is the most sensitive to the baffle position and dimension. For a given position of the baffle, the sloshing frequencies decrease with increase in the width of the baffle. The sensitivity of the sloshing frequencies to the width of the baffle increases as the baffle position shifts towards the free surface of the liquid. It is also found that the sloshing is significantly reduced when the baffle is installed very close to the free surface with *w/L* = 0.6.

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