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Employing Internal Flexible Wall as Mass Absorber in Tanks Subjected to Harmonic Excitations

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ABSTRACT

The possibility of employing internal wall as mass absorber in rectangular water storage tanks subjected to harmonic ground motion excitation is investigated in this paper. Internal walls are usually used to lengthen the water path in the tank that could also be used as mass absorber to control seismic demand on tank's exterior walls. Derivation of the response of the coupled system including rigid external walls, flexible internal wall and fluid field is in frequency domain. The responses of the tank are evaluated subjected to harmonic excitations. By tuning the dynamic behavior of the tank and the sloshing liquid by changing the mass and stiffness of internal flexible wall, it is shown that wave elevation and water pressure on external rigid walls can be significantly reduced.

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1. INTRODUCTION

Prior to the Alaska earthquake of 1964 where large-scale damage to tanks observed, it was believed that the liquid storage tanks are rigid and attention is mainly focused on the dynamic response of the contained liquid [1, 2].

Large seismic demand on tank walls usually results in the need for strengthening of the tank walls. To increase the water circulation path usually water tanks have internal walls. In the tanks not specifically designed for seismic loading, it was common perception among designers that the internal walls are not subjected to flexure (due to balancing hydrostatic liquid pressure on both sides of the wall), while external walls should be designed for liquid and soil pressure. This usually results in thicker sections for external walls compared to the internal ones. This paper investigates that how by tuning the mass of these flexible internal walls, it is possible to reduce seismic demand on nearly rigid external walls. By this way, it is possible to avoid strengthening the external walls that is a difficult job to do specially when it is not possible to shut down the tank from service for long time.

There are different methods for suppression of vibration and dissipation of energy in liquid storage tanks. These usually include internal wall or baffle and more recently wall flexibility.

The internal walls and baffles are primarily used as sloshing suppression devices, with no attention toreducing seismic demand on tank walls. The performance of rigid and flexible baffles on cylindrical containers was investigated by Abramson and Silverman [3]. Stephens [4] experimentally verified that flexible baffles could be more effective than rigid ones. Performing a series of experiments on tanks with and without baffles, Panigrahy et al. [5] studied the wall pressure and also required freeboard height. Hasheminejad et al. [6] investigated liquid sloshing in partially filled cylindrical liquid storage tanks. They considered the effect of different configurations of baffles on sloshing frequencies and also on impulsive and convective masses. Finally, they studied the effect of baffle in laterally excited tanks. Wu et al. [7] considering fluid nonlinearity and viscosity developed a numerical model accounting for vortex generation and shedding around baffles. They verified their

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numerical model with experimental results. Akyildiz et al. [8] experimentally investigated the effect of ring baffles in cylindrical tanks subjected to roll excitation. Takabatake et al. [9] accounting for failures observed in petroleum storage tanks during Tokachi-oki earthquake suggested and tested the performance of an internal wall. They found that the internal wall could effectively reduce the sloshing height for wide range of excitation frequencies. Bhavya et al. [10] improved the shape of ring baffles to reduce sloshing in satellite launch vehicle. They deigned and verified the performance of new baffles using finite element method.

The fluid-structure interaction could significantly change the dynamic characteristics of the coupled system. Many researchers including Yang [11], Minowa [12, 13] and Ghaemmaghami and Kianoush [14] studied the fluid-structure interaction effect on the dynamic response of liquid tanks incorporating wall flexibility, where the results show that the wall flexibility have a significant impact on seismic response of the liquid storage tanks. Hashemi et al. [15] developed a 3D model of flexible rectangular tank interacting with sloshing liquid. The model is based on Rayleigh-Ritz method. Finally, they derived an equivalent mechanical model for flexible tanks. Nicolici and Bilegan [16] coupled computational fluid dynamics (CFD) model with finite element method to study the effect of the wall flexibility. They concluded that wall flexibility magnifies the impulsive pressure. Cakir and Livaoglu [17] evaluated the seismic response of flexible back filled tanks using ANSYS. They found that backfill-fluid-structure interaction could significantly affect the lateral displacement of the tank. Tariverdilo et al. [18] using variational formulation studied the membrane and flexural stress in floating roofs of cylindrical liquid storage tanks. Shabani [19] investigated the stress pattern in tanks with single deck floating roofs subjected to ground motion acceleration. He studied the locations and magnitude of large stresses in the deck. Mirbagheri et al. [20] using finite element method investigated the wave equation near seawall. They derived the sloshing induced forces on the sea wall and effective depth of wave.

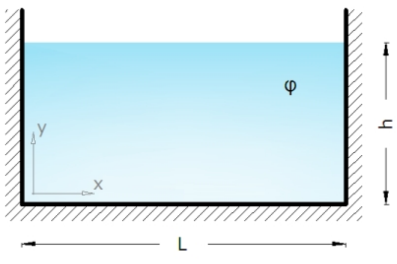


Figure 1. Schematic view of ordinary rigid tank

On the other hand, Frahm [21] introduced the first dynamic vibration absorber. This vibration control device was effective only when natural frequency of absorber was very close to the excitation frequency but its performance suffered a significant deterioration at other excitation frequencies. Ormondroyd and Den Hartog [22] improved the performance of the mass absorber extending its working frequency range. Mass absorbers are also used in tall buildings [23], long span bridges [24, 25] and railways [26] to control vibration and structural response.

The dynamic interaction of flexible container and sloshing liquid can also be used to control liquid sloshing. Anderson [27] investigated, the possibility of using container flexibility to control the liquid sloshing. The study performed using finite element method and confirmed experimentally. Gradinscak et al. [28] developed ANSYS model to study interaction of sloshing fluid with flexible wall.

In common application of internal walls, the aim is to effectively eliminate sloshing mode using nearly *rigid internal walls* to decrease the width of the tank. This paper investigates the possibility of using *flexible internal wall* of tank as mass absorber not to eliminate liquid sloshing, but to reduce seismic demand on the external walls. Velocity potential function is used to describe incompressible and inviscid fluid flow induced by ground motion excitation. The response of fluid-tank interaction is controlled by tuning the mass of flexible internal wall. The performance of the considered mass absorber is evaluated for different types of ground motion excitations.

2. FORMULATION

2. 1. Ordinary Rigid Tank Figure 1 depicts an ordinary rigid tank. For incompressible and inviscid fluid, fluid flow can be evaluated using velocity potential function φ satisfying the Laplace equation

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

The ground motion excitation $x_g(t)$ could be decomposed to its frequency components using Fourier transform:

$$x_0(\omega) = \int_{-\infty}^{+\infty} x_g(t) e^{-i\omega t} dt \tag{2}$$

where $x_0(\omega)$ is the amplitude of ground motion at frequency ω. Here discrete fast Fourier transform is used for numerical evaluation of this integral. Boundary conditions for potential function will be

$$\left.\frac{\partial\varphi}{\partial x}\right|_{x=0,l} = i\omega x_0 e^{i\omega t} \tag{3a}$$

$$\left.\frac{\partial \varphi}{\partial y}\right|_{y=0} = 0 \tag{3b}$$

$$g\frac{\partial \varphi}{\partial y} + \left.\frac{\partial^2 \varphi}{\partial t^2}\right|_{y=h} = 0 \tag{3c}$$

where l is the length of the tank and h is water height in the tank (Figure 1). The first boundary condition assumes the same lateral motion for the tank's rigid wall as those of ground motion, while the second boundary condition gives the impermeability condition on the tank's bottom side and the last boundary condition is the linearized free surface equation.Using the method of separation of variables and imposing boundary conditions (3b) and (3c), the potential function takes the following form

$$\varphi = \begin{bmatrix} \sum_{n=1}^{\infty} \begin{pmatrix} A_n \cosh \lambda_n x \\ + B_n \sinh \lambda_n x \end{pmatrix} \cos \lambda_n y \\ + \begin{pmatrix} A_0 \cos \lambda_0 x \\ + B_0 \sin \lambda_0 x \end{pmatrix} \cosh \lambda_0 y \end{bmatrix} e^{i\omega t} \tag{4}$$

where λ_n, λ_0 are the roots of the following characteristic equations

$$\begin{aligned} &\lambda_n \tan \lambda_n h + \frac{\omega^2}{g} = 0 \\ &\lambda_0 \tanh \lambda_0 h - \frac{\omega^2}{g} = 0 \end{aligned} \tag{5}$$

Applying the first boundary condition and using the orthogonality of eigen functions, the admissible solution for the potential function will be

$$\varphi(\omega) = \begin{bmatrix} \sum_{n=1}^{\infty} \frac{4 i \omega x_0 \sin \lambda_n h}{\lambda_n \left(\sin 2\lambda_n h + 2\lambda_n h\right)} \times \\ \begin{pmatrix} \frac{1 - \cosh \lambda_n l}{\sinh \lambda_n l} \cosh \lambda_n x \\ + \sinh \lambda_n x \end{pmatrix} \cos \lambda_n y \\ + \frac{4 i \omega x_0 \sinh \lambda_0 h}{\lambda_0 (\sinh 2\lambda_0 h + 2\lambda_0 h)} \times \\ \begin{pmatrix} \frac{\cos \lambda_0 l - 1}{\sin \lambda_0 l} \cos \lambda_0 x \\ + \sin \lambda_0 x \end{pmatrix} \cosh \lambda_0 y \end{bmatrix} e^{i\omega t} \tag{6}$$

Making use of linearized Bernoulli equation, the hydrodynamic pressure of fluid on the tank's wall could be evaluated as:

$$P(\omega) = \rho_f \omega^2 x_0 \begin{bmatrix} \sum_{n=1}^{\infty} \frac{4 \sin \lambda_n h}{\lambda_n \left(\sin 2\lambda_n h + 2\lambda_n h\right)} \times \\ \left(\frac{\cosh \lambda_n l - 1}{\sinh \lambda_n l}\right) \cos \lambda_n y + \\ \frac{4 \sinh \lambda_0 h}{\lambda_0 (\sinh 2\lambda_0 y + 2\lambda_0 h)} \times \\ \left(\frac{1 - \cos \lambda_0 l}{\sin \lambda_0 l}\right) \cosh \lambda_0 y \end{bmatrix} e^{i\omega t} \tag{7}$$

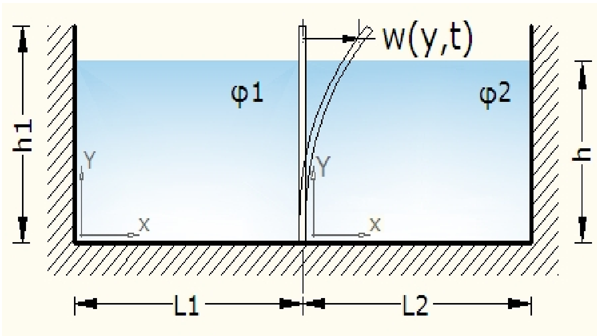


Figure 2. Rigid tank with flexible internal wall

Now, integrating the fluid pressure on tank wall, the total lateral force on the tanks walls will be

$$V(\omega) = \rho_f \omega^2 x_0 \begin{bmatrix} \sum_{n=1}^{\infty} \frac{4 \sin \lambda_n h}{\lambda_n^2 \left(\sin 2\lambda_n h + 2\lambda_n h\right)} \times \\ \left(\frac{\cosh \lambda_n l - 1}{\sinh \lambda_n l}\right) \sin \lambda_n h + \\ \frac{4 \sinh \lambda_0 h}{\lambda_0^2 (\sinh 2\lambda_0 y + 2\lambda_0 h)} \times \\ \left(\frac{1 - \cos \lambda_0 l}{\sin \lambda_0 l}\right) \sinh \lambda_0 h \end{bmatrix} e^{i\omega t} \tag{8}$$

2. 1. Rigid Tank With Flexible Internal Wall

Figure 2 depicts idealized model of coupled system including flexible internal wall of height h_1, interacting with a rectangular tank that is filled to the height of h, where the width of tank on two sides of flexible wall are l_1 and l_2. The external walls are assumed to be rigid. The internal flexible wall is employed as mass absorber. The boundary condition for bottom side of this wall is assumed to be clamped, while top side is free.

The vibration of wet internal wall is described by forced equilibrium equation of plate (Equation 9) and the fluid motion in both sides of the internal wall should satisfy the Laplace equation and corresponding boundary conditions (Equations 10 and 11)

$$\rho \ddot{w} + D \frac{\partial^4 w}{\partial y^4} = p - \rho \ddot{x}_g \tag{9}$$

$$\begin{aligned} &\nabla^2 \varphi_1 = 0 \\ &\left| \begin{array}{ll} \left.\frac{\partial \varphi_1}{\partial x}\right|_{x=0} = i\omega x_0 e^{i\omega t} \quad , \left.\frac{\partial \varphi_1}{\partial x}\right|_{x=l_1} = \frac{\partial w_t}{\partial t} & (a) \\ \left.\frac{\partial \varphi_1}{\partial y}\right|_{y=0} = 0 \quad , g\frac{\partial \varphi_1}{\partial y} + \left.\frac{\partial^2 \varphi_1}{\partial t^2}\right|_{y=h} = 0 & (b) \end{array} \right. \end{aligned} \tag{10}$$

$$\nabla^2\varphi_2 = 0$$

$$\left| \begin{array}{l} \left.\frac{\partial\varphi_2}{\partial x}\right|_{x=0} = \frac{\partial w_t}{\partial t} \;, \left.\frac{\partial\varphi_2}{\partial x}\right|_{x=l_2} = i\omega x_0 e^{i\omega t} \quad (a) \\ \left.\frac{\partial\varphi_2}{\partial y}\right|_{y=0} = 0 \quad , \left. g\frac{\partial\varphi_2}{\partial y} + \frac{\partial^2\varphi_2}{\partial t^2}\right|_{y=h} = 0 \quad (b) \end{array} \right. \tag{11}$$

where φ_1 and φ_2 are the velocity potential function of fluid on the left and right hand sides of flexible internal wall, respectively, ρ is mass per unit length, D is flexural stiffness of the plate and P is the hydrodynamic pressure of fluid on the tanks internal flexible wall, which could be evaluated employing following linearzed Bernoulli equation

$$p = -\rho_f \frac{\partial\varphi_1}{\partial t} + \rho_f \frac{\partial\varphi_2}{\partial t} \tag{12}$$

The total displacement of the plate w_t could be decomposed to ground motion displacement $x_g(t)$ and the plate deflection $w(y, t)$ as:

$$w_t(y,t) = x_g(t) + w(y,t). \tag{13}$$

Expanding the deflection of wet plate w (accounting for fluid-structure interaction) in terms of mode shapes of dry plate $\bar{w}_n(y)$ (ignoring fluid-structure interaction) (see e.g. [29, 30]), we have function:

$$w(y,t) = \sum_{n=1}^{\infty} E_n \bar{w}_n(y) e^{i\omega t} \tag{14}$$

To derive the mode shapes of dry plate, we consider the free vibration of dry plate and boundary conditions of clamped-free plate applying the boundary conditions, the natural frequency for n th mode and it's corresponding eigen function will be[31]

$$\begin{array}{l} \rho\ddot{w} + D\frac{\partial^4 w}{\partial y^4} = 0 \\ w(0,t) = \frac{\partial w}{\partial y}(0,t) = \frac{\partial^2 w}{\partial y^2}(h_1,t) = \frac{\partial^3 w}{\partial y^3}(h_1,t) = 0 \end{array} \tag{15}$$

$$\begin{array}{l} \omega_n = \beta_n^2\sqrt{D/\rho} \\ \bar{w}_n(y) = \begin{pmatrix} \mu_n(\sinh\beta_n y - \sin\beta_n y) \\ -\cosh\beta_n y + \cos\beta_n y \end{pmatrix} \end{array} \tag{16}$$

where β_n could be obtained by solving the following characteristic equation[31]

$$\cos(\beta_n h_1) \times \cosh(\beta_n h_1) = -1 \tag{17}$$

In Equation (16) μ_n is defined as

$$\mu_n = \frac{\cosh(\beta_n h_1) + \cos(\beta_n h_1)}{\sinh(\beta_n h_1) + \sin(\beta_n h_1)}. \tag{18}$$

Now, utilizing the method of separation of variables in Equations (10, 11) and imposing boundary conditions (10b, 11b), the solution for velocity potential functions become

$$\varphi_1 = \begin{bmatrix} \sum_{n=1}^{\infty}\begin{pmatrix} A_n\cosh\lambda_n x \\ +B_n\sinh\lambda_n x \end{pmatrix}\cos\lambda_n y \\ +\begin{pmatrix} A_0\cos\lambda_0 x \\ +B_0\sin\lambda_0 x \end{pmatrix}\cosh\lambda_0 y \end{bmatrix} e^{i\omega t} \tag{19}$$

$$\varphi_2 = \begin{bmatrix} \sum_{n=1}^{\infty}\begin{pmatrix} C_n\cosh\lambda_n x \\ +D_n\sinh\lambda_n x \end{pmatrix}\cos\lambda_n y \\ +\begin{pmatrix} C_0\cos\lambda_0 x \\ +D_0\sin\lambda_0 x \end{pmatrix}\cosh\lambda_0 y \end{bmatrix} e^{i\omega t} \tag{20}$$

Imposing the boundary conditions (10a, 11a) and using the orthogonal properties of eigenfunctions, leads to the following equations for modal amplitudes

$$\begin{array}{ll} \left| \begin{array}{l} A_0 = i\omega[\hat{B}_0 + \sum_{k=1}^{\infty} a_{0k}E_k] \\ A_m = i\omega\left[\hat{B}_m + \sum_{k=1}^{\infty} a_{mk}E_k\right] \end{array}\right. & (a) \\ \left| \begin{array}{l} B_0 = i\omega\bar{B}_0 \\ B_m = i\omega\bar{B}_m \end{array}\right. & (b) \\ \left| \begin{array}{l} C_0 = i\omega[\tilde{B}_0 + \sum_{k=1}^{\infty} c_{0k}E_k] \\ C_m = i\omega[\tilde{B}_m + \sum_{k=1}^{\infty} c_{mk}E_k] \end{array}\right. & (c) \\ \left| \begin{array}{l} D_0 = i\omega[\bar{B}_0 + \sum_{k=1}^{\infty} b_{0k}E_k] \\ D_m = i\omega[\bar{B}_m + \sum_{k=1}^{\infty} b_{mk}E_k] \end{array}\right. & (d) \end{array} \tag{21}$$

where

$$\begin{array}{l} \bar{B}_0 = \frac{4x_0\sinh\lambda_0 h}{\lambda_0(\sinh 2\lambda_0 h + 2\lambda_0 h)} \\ \bar{B}_m = \frac{4x_0\sin\lambda_m h}{\lambda_m(\sin 2\lambda_m h + 2\lambda_m h)} \\ \hat{B}_0 = \frac{(\cos\lambda_0 l_1 - 1)}{\sin\lambda_0 l_1}\bar{B}_0 \\ \hat{B}_m = \frac{(1 - \cosh\lambda_m l_1)}{\sinh\lambda_m l_1}\bar{B}_m \\ \tilde{B}_0 = \frac{(\cos\lambda_0 l_2 - 1)}{\sin\lambda_0 l_2}\bar{B}_0 \\ \tilde{B}_m = \frac{(1 - \cosh\lambda_m l_2)}{\sinh\lambda_m l_2}\bar{B}_m \end{array} \tag{22}$$

and

$$
\begin{aligned}
q_{0k} &= \int_0^h \overline{w}_k(y)\cosh\lambda_0 y\,dy \\
q_{mk} &= \int_0^h \overline{w}_k(y)\cos\lambda_m y\,dy \\
b_{0k} &= \frac{4q_{0k}}{(\sinh 2\lambda_0 h + 2\lambda_0 h)} \\
b_{mk} &= \frac{4q_{mk}}{(\sin 2\lambda_m h + 2\lambda_m h)} \\
a_{0k} &= -\frac{b_{0k}}{\sin\lambda_0 l_1} \quad ,a_{mk} = \frac{b_{mk}}{\sinh\lambda_m l_1} \\
c_{0k} &= \frac{b_{0k}}{\tan\lambda_0 l_2} \quad ,c_{mk} = -\frac{b_{mk}}{\tanh\lambda_m l_2}.
\end{aligned}
\tag{23}
$$

Using potential functions of Equations (19, 20) and (14) for evaluation of pressure and plate equilibrium equation and employing the orthogonality of the dry plate's eigen-functions, we have

$$
\begin{aligned}
&E_m(-\rho\omega^2 + D\beta_m^{\ 4})\int_0^{h_1}\overline{w}_m^{\ 2}(y)\,dy = \rho_f\, i\,\omega \times \\
&\left[\begin{aligned}
&-\sum_{n=1}^{\infty}\begin{pmatrix} A_n\cosh\lambda_n l_1 \\ +B_n\sinh\lambda_n l_1\end{pmatrix}\int_0^{h_1}\cos\lambda_n y\times\overline{w}_m(y)\,dy \\
&-\begin{pmatrix} A_0\cos\lambda_0 l \\ +B_0\sin\lambda_0 l\end{pmatrix}\int_0^{h_1}\cosh\lambda_0 y\times\overline{w}_m(y)\,dy \\
&+\sum C_n\int_0^{h_1}\cos\lambda_n y\times\overline{w}_m(y)\,dy + \\
&C_0\int_0^{h_1}\cosh\lambda_0 y\times\overline{w}_m(y)\,dy
\end{aligned}\right] \\
&+\rho x_0\omega^2\int_0^{h_1}\overline{w}_m(y)\,dy
\end{aligned}
\tag{24}
$$

Considering E_j as column vector E, Equation (24) could be rewritten in terms of modal amplitudes in matrix form as

$$
\{K-(M+M_a)\omega^2\}\times E = p \tag{25}
$$

here the terms K and M are associated with stiffness and mass of plate, respectively and M_a is added mass of the plate. In this equation P can be expressed as sum of two components P_F and P_G which are related to external dynamic forces due to fluid pressure and that due to ground motion, respectively.

$$
\begin{aligned}
&K = diag(K_j) \ \rightarrow K_j = D\beta_j^4 f_j && (a) \\
&M = diag(M_j) \rightarrow M_j = \rho f_j && (b) \\
&M_a = \left[M_{jn}\right] \\
&\rightarrow M_{jn} = \rho_f\sum_{m=0}^{\infty}\sum_{n=1}^{\infty}(g_{jm}a_{mn} - p_{jm}c_{mn}) && (c)
\end{aligned}
\tag{26}
$$

$$
\begin{aligned}
&p_F = [p_{Fj}] \\
&\rightarrow p_{Fj} = \rho_f\omega^2\sum_{m=0}^{\infty}(g_{jm}\hat{B}_m + h_{jm}\overline{B}_m - p_{jm}\tilde{B}_m) \ (a) \\
&p_G = [p_{Gj}] \rightarrow p_{Gj} = \rho\omega^2 r_j \qquad (b)
\end{aligned}
\tag{27}
$$

Where

$$
\begin{aligned}
f_j &= \int_0^{h_1}\overline{w}_j^2(y)\,dy \qquad j,m = 1,2,\cdots \\
r_j &= \int_0^{h_1}\overline{w}_j(y)\,dy \\
p_{j0} &= \int_0^{h_1}\cosh\lambda_0 y\times\overline{w}_j(y)\,dy \\
p_{jm} &= \int_0^{h_1}\cos\lambda_m y\times\overline{w}_j(y)\,dy \\
g_{j0} &= \cos\lambda_0 l_1\times p_{j0} \quad ,g_{jm} = \cosh\lambda_m l_1\times p_{jm} \\
h_{j0} &= \sin\lambda_0 l_1\times p_{j0} \quad ,h_{jm} = \sinh\lambda_m l_1\times p_{jm}
\end{aligned}
\tag{28}
$$

3. VERIFICATION

In this section, we verify the derivation presented in the previous section. External wall pressure distribution under lateral excitation is compared with those of Ibrahim [32], where the walls are assumed to be rigid. Pressure distribution of rigid external wall, for three different harmonic excitations is shown in Figure 3. The responses are derived for very stiff internal wall, where the stiffness of the flexible internal wall is artificially increased. For nearly rigid internal wall the resulting water pressure follows with good accuracy those of rigid tank.

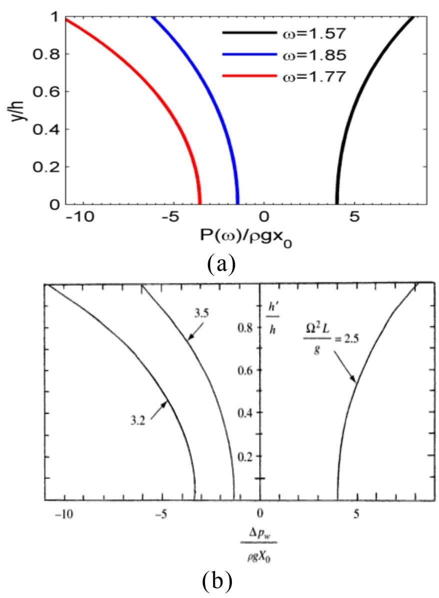


Figure 3. Exterior wall pressure distribution for three different excitation frequency ω. a) Nearly rigid internal wall, b) from Ibrahim [32].

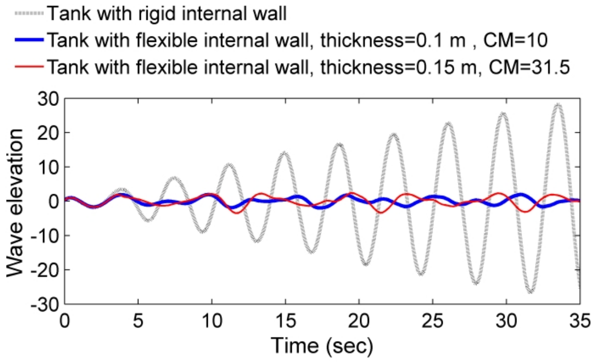


Figure 4. Response history of wave elevation adjacent to the rigid wall subjected to harmonic excitation of period 3.7 s.

4. SIMULATIONS RESULTS

Dimensional properties of the tanks considered in the simulations-including the rigid tank and the tank with external rigid walls and internal flexible wall- are given in Table 1. The containing fluid is considered to be water with ρ_f of 1000 kg/m^3 . For rigid tank, the first natural period of sloshing is 3.74 sec. Table 2 gives the properties of the internal wall used in the simulations.

In order to control the fluid-tank interaction in the case of tank with flexible internal wall, the mass of the internal wall is tuned. For this purpose, the mass of this wall is increased by factor denoted by CM.

Subjecting the tank to harmonic ground displacement with period of 3.7 sec and considering one percent damping, the response history of the wave elevation adjacent to the rigid wall for the rigid tank and the tank with internal flexible wall are depicted in Figure 4. As could be seen, for the tank with tuned flexible internal wall the amplitude of wave elevation is significantly lower than that for the rigid tank.

Figure 5 shows the evolution of different response parameters, including wave elevation and base shear, for changing values of tuned mass (CM). This figure could be used to find best value for tuned mass that minimizes interested response parameter.

TABLE 1. Properties of fluid-tank systems

Simple rigid tank		Rigid tank with internal flexible wall			
$h(m)$	$L(m)$	$h(m)$	$h_1(m)$	$L_1(m)$	$L_2(m)$
5	10	5	6	10	10

TABLE 2. Properties of considered internal flexible walls

Thickness (m)	flexural stiffness, D (MN.m)	unit weight, ρ (kg/m^2)
0.15	2.812	367.5

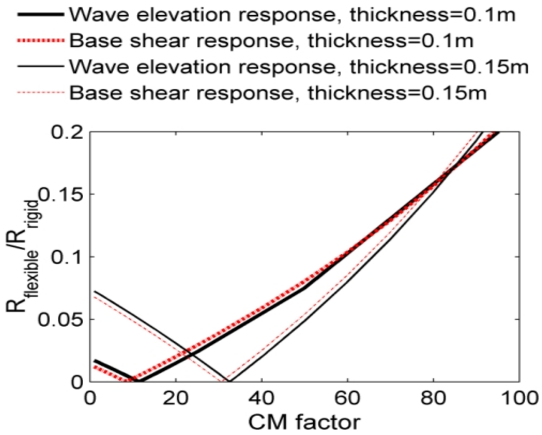


Figure 5. Variation of different response parameters with CM factor for the tanks having flexible internal wall of different thicknesses

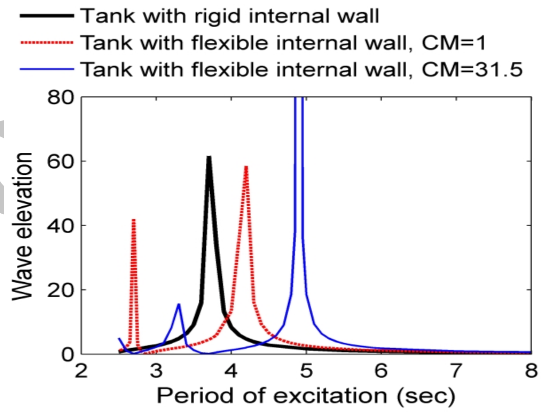


Figure 6. Frequency response curve of tanks with flexible internal wall

Figure 6 shows wave elevation for the rigid tank and the tanks with flexible internal wall with different tuned mass (CM=1 and CM=31.5). Accounting for wall flexibility and increasing the mass of the wall (for tuning purpose) shifts the natural period of the coupled system toward longer periods. As could be seen, wave elevation considering flexibility of internal wall (CM=1) increases compared to the rigid tank, however, it is possible to significantly reduce this wave elevation by tuning the mass of flexible wall in the periods ranging from zero to 4 sec.

As shown in this figures, it is also possible to vanish the response amplitude at a certain frequency range of interest by tuning the mass of internal wall. For CM=31.5, the wave elevation near natural period of rigid tank decreases drastically. As could be inferred from Figure 5 the same pattern of frequency response evolution exists for wall shear and moment.

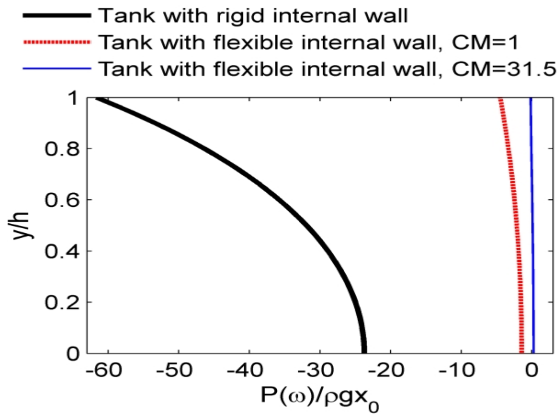


Figure 7. Exterior wall pressure distribution for rigid

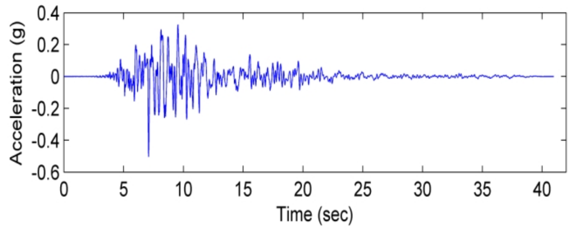
Figure 7 compares the external wall pressure distribution of tank having rigid internal wall with those of tank having flexible internal wall of different masses. As could be seen, the hydrodynamic pressure on external rigid wall of tank can be significantly reduced by employing an internal flexible wall. For the tanks with tuned internal flexible wall, this pressure becomes nearly zero.

To assess the performance of the proposed system in reduction of seismic demand on external walls, we evaluate the response of tank to 090 component of 1995 Kobe ground motion record. Figure 8 depicts the time history and Fourier decomposition of the excitation.

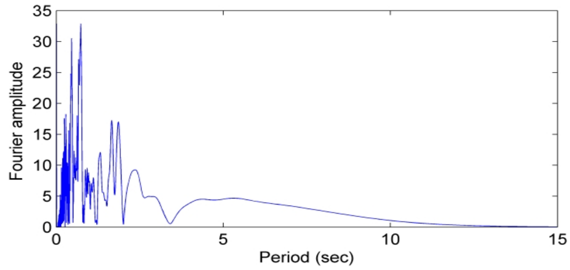
Figure 9a shows the response history for wave elevation evaluated for two different masses (CMs) on flexible wall. As could be seen, appreciable reduction in wave elevation could be observed through mass tuning on flexible internal wall.

Energy balance requires that in tuned case (CM=90) the reduction in sloshing should be balanced by increase in the energy in other form. Figure 9b depicts the response history at the top of flexible internal wall. As could be seen there is increase in the displacement of the wall in the case of CM=90 compared to the case of CM=1. This indicates that in tuned case ground motion energy instead of sloshing is absorbed in the form of displacement of internal wall.

Mass tuning of the internal wall provides a means for reduction of response parameters in the interested frequency range. The response parameters could include wave elevation and shear and moment demand on tank's exterior walls. On the other hand, review of response spectrum of different ground motions (Chopra [33]) and also design response spectrum of codes (e.g. NEHRP [34]) reveals that energy of the ground motions mainly concentrated in periods lower than 4 sec. Considering the shape of design or response spectrums, and employing mass tuning it is possible to significantly reduce seismic demand on tanks wall.

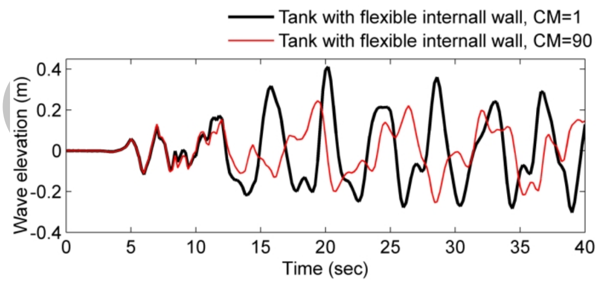


(a)

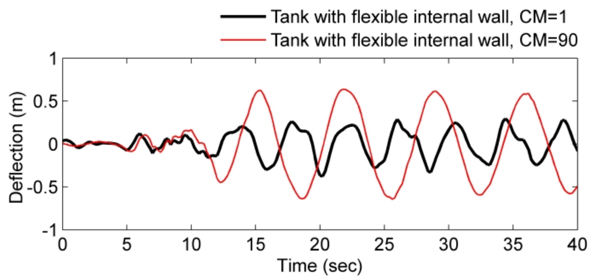


(b)

Figure 8. Kobe ground motion record, a) time history, b) Fourier decomposing.



(a)



(b)

Figure 9. Response history of wave elevation and internal wall tip displacement for two different masses on flexible wall for Kobe ground motion record.

5. CONCLUSION

Employment of flexible internal wall as vibration absorber in rectangular tanks subjected to harmonic excitations is investigated. Derivation of the response of the coupled system accounting for fluid-tank interaction is in frequency domain. The response of the tuned system, including wave elevation, base shear and pressure distribution are derived and compared with those of the rigid tank. It is shown that tuning shifts natural periods of the system towards longer periods and makes it possible to simultaneously suppress different response parameters.

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Employing Internal Flexible Wall as Mass Absorber in Tanks Subjected to Harmonic Excitations

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چکیده

در این مقاله امکان به کارگیری جاذب جرم برای کنترل پاسخ دینامیکی آب در مخازن ذخیره‌ی آب مکعب مستطیلی شکل بررسی قرار می‌شود. این مخازن، اغلب به دلیل نیازهای مربوط به کاربری دارای دیواره داخلی هستندکه می‌توان از این دیوار انعطاف پذیر به عنوان جاذب‌جرم برای کنترل رفتار مخزن استفاده نمود. پاسخ سیستم در بر گیرنده اندرکنش دیواره‌های صلب خارجی، دیواره‌ی انعطاف‌پذیر داخلی و سیال در حوزه‌ی فرکانس استخراج شده و پاسخ مخزن به تحریکات هارمونیکی مختلف مورد ارزیابی قرار گرفته است. نتایج نشانگر آن استکه با تنظیم جرم و سختی دیواره‌ی انعطاف‌پذیر داخلی در یک بسامدمشخص می‌توان پارامترهای پاسخ سیستم شامل ارتفاع موج آب و فشار آب بر روی دیواره‌ی صلب خارجی را برای محدوده بسامدکه تحریکات زلزله دارای محتوای بسامدعمده در آن هستند به نحو محسوسی کاهش داد.

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