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Tuning mass of internal flexible wall to reduce seismic demand on exterior walls of liquid storage tanks

J. Mousavi, S. Tariverdilo *

Department of Civil Engineering, University of Urmia, Urmia, Iran

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ABSTRACT

This paper investigates the possibility of tuning internal walls of rectangular water storage tanks to reduce seismic demand on the tank external walls. Derivation of the response of the coupled system including rigid external walls, flexible internal wall and fluid field is in frequency domain. Response of the tank is evaluated for different kinds of ground motion records, including near-source and long-period far-field records. It is shown that when the flexibility of the internal wall leads to substantial increase in seismic demand, by tuning the mass of internal flexible wall, it is possible to reduce the seismic demand on the external walls.

1. Introduction

Liquid storage tanks designed before adoption of modern codes usually require retrofit to accommodate large seismic forces on tank's wall. Usual retrofit measures incorporate increase in strength and stiffness of tank walls to accommodate the seismic demand that is not always a feasible option. Other than strengthening, there are two usual ways of reducing liquid sloshing or seismic demand on tank walls: introducing a baffle (rigid or flexible) that is mainly used to reduce liquid sloshing, and employing wall flexibility to control the seismic demand.

A common way to suppress sloshing is to introduce different forms of baffles. The performance of rigid and flexible baffles on cylindrical containers was investigated by Abramson and Silverman [1]. Popov et al. [2] derived governing equations for liquid sloshing in compartmented and baffled rectangular road containers adopting the 2-D Navier–Stokes equation for incompressible fluid. They explored the effect of a range of parameters on the sloshing response of rigid road containers due to braking and steady cornering movements. Panigrahy et al. [3] experimentally considered the pressure on the tank wall and wave elevation in tanks with and without baffles. Dodge [4] and Ibrahim [5] provide comprehensive review of works done on baffles as sloshing suppression devices.

Stephens [6] experimentally showed that flexible baffles could be even more effective than rigid ones. Noorian et al. [7] employing modal analysis on the structure and the boundary element method on the fluid, examined the interaction of fluid and structure with flexible baffles. They studied the effect of flexibility of baffles on sloshing frequencies and structure's vibration frequencies. Koh et al. [8] studied the performance of a constrained floating baffle as sloshing suppression device using a newly developed consistent particle method, which is introduced to overcome the problem of pressure fluctuation in fluid–structure interaction. It must be noted that the main objective for employing baffles is the suppression of sloshing response and reduction of the seismic demand on the tank walls is not the primary purpose.

Haroun [9] studied the seismic response of flexible cylindrical liquid storage tanks. He developed a mechanical model similar to the well-known Housner [10] model applicable for flexible tanks. Tedesco and Kostem [11] also investigated the vibration characteristics and seismic response of flexible cylindrical liquid storage tanks. They found that flexibility has only appreciable impact on impulsive pressure, while convective pressure is not affected by wall flexibility. Ozdemir et al. [12] using their experimental results verified finite element simulations accounting for different form of nonlinearity in structure.

Kianoush and coworkers investigated the effect of wall flexibility on the seismic demand in tank walls. Ghaemmaghami and Kianoush [13] used the finite element method to account for wall flexibility. They showed that due to dynamic magnification, the impulsive pressure increases substantially in mid height of the wall. Hashemi et al. [14], employing weak coupling between impulsive and convective modes of response, decomposed the 3D

* Corresponding author. Tel.: +98 441 2972947; fax: +98 441 2972901.
E-mail addresses: jahanmousavi@yahoo.com (J. Mousavi), s.tariverdilo@urmia.ac.ir (S. Tariverdilo).

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response in terms of these modes for rectangular liquid storage tanks. They used rigid boundary condition for the convective mode, but accounted for wall flexibility in the impulsive mode. They also developed a mechanical model that accounts for wall flexibility. Kianoush and Ghaemmaghami [15] developing a 3D model accounting for wall and soil flexibility explored the effect of soil–structure–liquid on the sloshing response for different ground motions.

The dynamic interaction of a flexible container and sloshing liquid can also be used to control liquid sloshing. Anderson [16] investigated the possibility of using a flexible container to control the liquid sloshing. The study was performed using the ANSYS finite element code and confirmed experimentally. Later Guzel et al. [17,18] and Gradinscak [19] elaborated on the potential of employing wall flexibility to reduce sloshing in flexible containers.

Rectangular storage tanks usually have internal walls to lengthen the water path in this tank. This prevents outlet flow to be affected by disturbance of the inlet flow. This paper investigates the possibility of employing mass tuning of internal flexible walls as a retrofit means, to reduce the seismic demand on the tank external walls. For incompressible and inviscid fluid, the fluid oscillation induced by ground motion excitation is described using the velocity potential function. Assuming rigid external walls, tuning of the flexible internal wall is used to control the response of the coupled system. The performance of the coupled system is evaluated for different kinds of ground motion records.

2. Formulation

Fig. 1 depicts the idealized model of the coupled system including a flexible internal wall of height h_1, interacting with a rectangular tank that is filled to a height h, where the lengths of the tank on two sides of the flexible wall are l_1 and l_2. The external walls are assumed to be rigid.

To evaluate the response of the tank to a general ground excitation, the ground motion excitation $x_g(t)$ can be decomposed into its frequency components using the Fourier transform

$$x_0(\omega) = \int_{-\infty}^{+\infty} x_g(t) e^{-i\omega t} dt \tag{1}$$

where $x_0(\omega)$ is the component of ground motion at frequency ω. For numerical evaluation of this integral the fast Fourier transform procedure is used.

In this study the internal wall is employed as a mass absorber. The boundary condition for the bottom side of this wall is assumed to be clamped, while the top side is free. It is a common assumption to expand the deflection of the wet wall (accounting for fluid–structure interaction) in terms of mode shapes of the dry wall (ignoring fluid–structure interaction) (e.g. [20,21]). To derive the mode shapes of a dry wall, we consider its free vibration equation of motion

$$\rho \ddot{w} + D \frac{\partial^4 w}{\partial y^4} = 0 \tag{2}$$

where w is the deflection of the wall, ρ is mass per unit length and D is the flexural stiffness of the wall. The boundary conditions for a clamped-free wall are

$$w(0,t) = \frac{\partial w}{\partial y}(0,t) = \frac{\partial^2 w}{\partial y^2}(h_1,t) = \frac{\partial^3 w}{\partial y^3}(h_1,t) = 0 \tag{3}$$

Applying these boundary conditions, the natural frequency for the nth mode will be [22]

$$\omega_n = \beta_n^2 \sqrt{D/\rho} \tag{4}$$

where β_n values could be obtained by solving the following characteristic equation [22]

$$\cos(\beta_n h_1) \times \cosh(\beta_n h_1) = -1 \tag{5}$$

Now the nth eigen-function takes the following form

$$\bar{w}_n(y) = \mu_n(\sinh \beta_n y - \sin \beta_n y) + (-\cosh \beta_n y + \cos \beta_n y) \tag{6}$$

here μ_n is

$$\mu_n = \frac{\cosh \beta_n h_1 + \cos \beta_n h_1}{\sinh \beta_n h_1 + \sin \beta_n h_1} \tag{7}$$

The fluid motion in both sides of the internal wall should satisfy the Laplace equation

$$\nabla^2 \varphi_1 = 0 \tag{8a}$$

$$\nabla^2 \varphi_2 = 0 \tag{8b}$$

where φ_1 and φ_2 are the velocity potential function of the fluid on the left and right hand sides of flexible internal wall, respectively. The boundary conditions for φ_1 will be

$$\left.\frac{\partial \varphi_1}{\partial x}\right|_{x=0} = i\omega x_0 e^{i\omega t} \tag{9a}$$

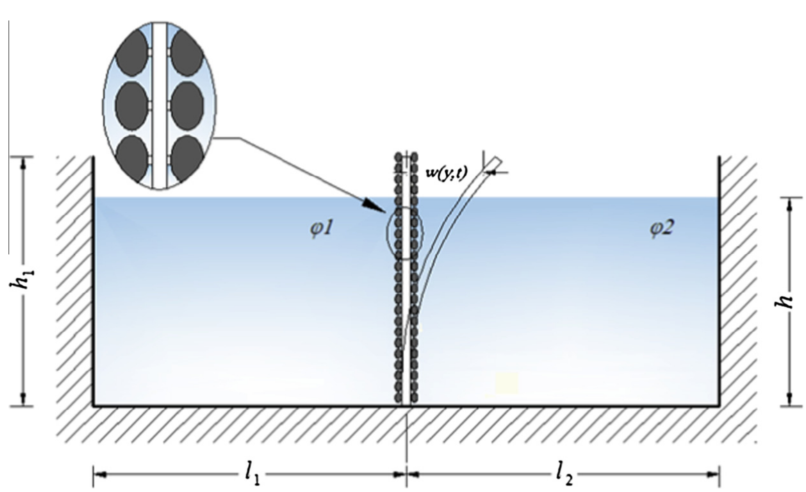

Fig. 1. Rigid tank with flexible internal wall.