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# Numerical investigation of a vertically baffled rectangular tank under seismic excitation

Mohammad Ali Goudarzi [a,*], Pouya Nourae Danesh [b]

[a] Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), No. 21, Arghavan St., North Dibajee, Farmanieh, Tehran, Iran
[b] International Institute of Earthquake Engineering and Seismology, Tehran, Iran

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ABSTRACT

The damping effect of the vertical baffles inside a liquid storage tank is studied in this paper. A numerical model based on the finite volume method is established and used to evaluate the accuracy of an analytical model developed to estimate the hydrodynamic damping caused by the vertical wall bounded baffles. For this purpose, several full scale baffled tanks with different aspect ratios are numerically analyzed. The numerical results were then used to validate the analytical model. The reduction in sloshing wave height caused by the baffles is estimated for selected tanks subjected to the seismic excitations. Finally, a simple procedure to estimate the reduction in sloshing amplitude due to the presence of baffles is proposed and validated using the time history numerical results.


## 1. Introduction

Sloshing is the free surface motion inside a liquid container caused by any disturbance to partially filled liquid containers. Detecting the sloshing phenomenon has various complex aspects some of which (e.g., nonlinearity for example) are a subject unto itself (Goudarzi and Sabbagh-Yazdi, 2012). On the other hand, investigating the sloshing effects has also been the focus of many researches. For example, the liquid sloshing may cause additional forces exerted on the tank roof (Goudarzi et al., 2010a) and walls, and it may lead to the structural failure or other types of instabilities. A sufficient freeboard is often provided to prevent sloshing impact on the tank roof by allowing the liquid to slosh freely in upper part of the tank. However, in most of the tanks especially those with small tank aspect ratio (i.e., height to length ratio), providing a freeboard leads to uneconomical design.

As another alternative, slosh suppression devices can be employed to damp the liquid motions and prevent sloshing damages. Several types of slosh suppression devices have been employed or undergone consideration in various applications to increase the damping of liquid sloshing. Due to the simple installation and high performance, baffles are most effective internal components used in many practical problems. Extensive investigations have been carried out to study the sloshing suppression effects of various types of baffles. The majority of these studies have been performed based on experimental methods.

From an analytical viewpoint, the baffle effects are usually represented as the damping ratio in the mathematical models. Goudarzi et al. (2010b) developed an analytical model based on the velocity potential formulation and linear wave theory to

* Corresponding author.
*E-mail address:* m.a.goodarzi@iiees.ac.ir (M.A. Goudarzi).

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estimate the hydrodynamic damping ratio of liquid sloshing for wall bounded baffles. A series of experiments were carried out with a rectangular liquid tank excited by harmonic oscillation in order to evaluate the accuracy of analytical solutions. Maleki and Ziyaeifar (2008) also developed an analytical solution using Laplace's differential equation to estimate the damping ratio of liquid sloshing in baffled tanks undergoing horizontal excitation. This method involved the assessment of a dissipated fraction of total sloshing oscillation energy caused by the flow separation around the baffles. A series of experiments employing a tank model on a shake table were carried out to validate the theoretically predicted damping ratio (Maleki and Ziyaeifar, 2008). They also considered the effectiveness of the baffles for seismically isolated cylindrical liquid storage tanks (Maleki and Ziyaeifar, 2007). Panigrahya et al. (2009) carried out a series of experiments on a square tank with and without baffles attached to a shaking table. Pressure and displacement were measured under various excitation frequencies of the shaking table and fill levels in the tank.

Zahrai et al. (2012) experimentally studied a type of tuned liquid damper with some installed rotatable baffles. The main idea behind installation of such baffles was to compensate the potential mistuning of the tuned liquid damper and to make it easier to convert them to a semi-active damper (Zahrai et al., 2012).

The numerical methods are more efficient than the experimental methods for the complex problems especially for real scale tanks. The fluid flow field inside a tank equipped by the baffles is quite complicated and its simulation demands extensive computational efforts. However, most of the previous researchers employed the computational methods to investigate the behavior of the baffled tanks. Hasheminejad and Aghabeigi (2009) introduced a two dimensional hydrodynamic analysis based on the linear potential theory to study the natural sloshing frequencies of transverse modes in a half-filled non-deformable horizontal cylindrical container of elliptical cross section. A pair of inflexible horizontal baffles of arbitrary extension positioned at the free surface was considered. The Gauss–Laguerre quadrature formula was used to approximate the integral Eigen-Problem obtained in the un-baffled tank. Hasheminejad and Mohammadi (2011) also studied the sloshing characteristics of transverse oscillation modes in a circular cylindrical baffled container. The solution was obtained by the method of successive conformal coordinate transformations, leading to standard truncated matrix eigenvalue problems on rectangular regions which were then solved numerically for the resonance Eigen-frequencies.

Sygulski (2011) investigated the natural frequencies and mode shapes of liquid sloshing in three dimensional baffled tanks. The boundary element method was used to solve the considered problem. The baffles were treated as double layers immersed in liquid. Belakroum et al. (2010) also numerically studied the damping effect of the baffles on sloshing in tanks partially filled with liquid. The studied phenomena formulation is based on an arbitrary Lagrangian–Eulerian description of the governing equations. The stabilized finite element method known as Galerkin least square was used in their study.

Wu et al. (2012) used a time-independent finite difference scheme with fictitious cell technique to study viscous fluid sloshing in 2D tanks with baffles. The governing equations in a moving coordinate system were derived and mapped onto a time-independent and stretched domain. An experiment setup was also made to validate the numerical sloshing results in a tank with baffles. Cho et al. (2005) investigated the numerical analysis of the resonance characteristics of liquid sloshing in a 2-D baffled tank subjected to the forced lateral excitation. Sloshing flow was formulated based on the linearized potential flow theory. A finite element method was developed for the resonant sloshing analysis in frequency domain.

Akyildız and Erdem Ünal (2006) carried out a numerical and experimental research on the pressure variations and three-dimensional effects on liquid sloshing loads in a moving partially filled rectangular tank. A numerical algorithm based on the volume of fluid technique was used to study the non-linear behavior and damping characteristics of liquid sloshing for several configurations of both baffled and un-baffled tanks.

Three-dimensional liquid sloshing in a baffled tank was also considered using the numerical models (Liu and Lin, 2009). The second-order volume-of-fluid method was used to track the distorted and broken free surface. The baffles in the considered tank were modeled by the virtual boundary force method. Xue and Pengzhi (2011) developed another three-dimensional numerical model to study viscous liquid sloshing in a tank with internal baffles. A numerical technique named virtual boundary force method was used to model the internal baffles with complex geometries. In the mentioned study, laboratory experiments were also conducted for non-linear sloshing in a rectangular tank with and without vertical baffles. Liquid sloshing in a 3D prismatic tank with different ring baffle arrangements were further investigated under near-resonant excitations of surge and pitch motions.

Biswal and Bhattacharyya (2010) considered the dynamic interaction between the liquid and elastic tank baffle system to evaluate the coupled response of liquid and tank baffle system using the finite element method. The finite element equations of liquid motion and structure domains were numerically integrated by Newmark integration scheme. The interaction effect between the two fields was studied by transferring the structural normal acceleration to the liquid domain and liquid pressure to the structure domain. Effects of different parameters, such as composite baffles, lamination scheme on the slosh frequencies, and coupled vibration frequencies in the liquid filled composite tanks were studied.

Hosseini et al. (2013) presented a method for reducing the analysis duration based on conducting several dynamic analysis cases by using ANSYS-CFX for rectangular tanks of various dimensions, subjected to seismic excitations. They used neural network to create simple relationships between the dominant frequency and amplitude of the base excitations and the maximum level of liquid in the tank during the sloshing (Hosseini et al., 2013).

Although many studies have been performed on the baffled tanks, the seismic behaviors of liquid tanks equipped by the baffles are rarely investigated. In a previous study, Goudarzi et al., 2010b developed an analytical method for evaluating the damping effects of vertical baffles inside a rectangular container. The results of the analytical solution were validated by experimental measurements on small scale tanks (Goudarzi et al., 2010b). This paper complements the previous study in