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Numerical evaluation of hydrodynamic damping due to the Upper Mounted Baffles in real scale tanks

M.A. Goudarzi [a,*], P. Farshadmanesh [b]

[a] Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), No. 21, Arghavan St., North Dibajee, Farmanieh, Tehran, Iran
[b] Illinois Institute of Technology, 3300 South Federal Street Chicago, USA

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ABSTRACT

In this study, the hydrodynamic damping effects of Upper Mounted Baffles (UMB) used in the real scale liquid tanks are numerically investigated. In this regard, the paper follows three main purposes. First, the accuracy of the analytical model developed by the author is examined for full scale applications. In this regard, the tanks equipped by UMB with various dimensions and locations are numerically analyzed in free vibration mode. Then, the numerical results are compared with an analytical solution results, and the validity of the analytical formulation for using in real applications is discussed. Second, the seismic efficiency of UMB is considered, and the reduction of the sloshing wave height due to the presence of the UMB is examined under several earthquake excitations. Finally, a seismic design procedure is proposed to evaluate the effect of UMB on the suppression of sloshing in a liquid tank, and its predictions are compared with the results of numerical analysis.

1. Introduction

Sloshing in partially filled liquid containers is a common phenomenon which can generally cause huge financial and criminal damage. This phenomenon is mostly the result of the horizontal excitation in moving container. Although, there are lots of previous researches on this area, investigation about the sloshing caused by the earthquake excitation is rare. The seismically liquid sloshing has some important aspects which were considered by the authors in their previous researches. One of these features is the nonlinear effect of free surface motion, specially, when the amplitude wave height is large enough. This effect increases the liquid wave height calculated by analytical linear solution. The nonlinear sloshing under harmonic and seismic excitations was investigated by Goudarzi and Sabbagh-Yazdi [14].

In seismic design of liquid tanks, often, an estimate of the maximum wave amplitude expected during the earthquake motion is only required. When surface tension is negligible, the maximum acceleration at the peak height always has to remain positive. Otherwise the fluid particle would tear off from the surface. Therefore, the maximum sloshing wave height can be no larger than $\eta_{max} = g/\omega^2$ and the maximum usually occurs at the tank walls. Where g is the effective gravitational acceleration, η_{max} is the wave amplitude, and ω is the slosh natural frequency. In fact, splashing, breaking waves, and even rotary sloshing would probably occur for such large amplitude.

In the case of seismic design of storage tank, due to the economic concerns, the provided freeboard is too smaller than such a large sloshing wave height. Therefore, a better estimate, which can be used as we discuss about sloshing wave height is that the maximum amplitude would not be more than about 10% of the tank diameter, beyond which splashing and rotary sloshing will occur.

Another feature of liquid sloshing in liquid tanks is the impaction of liquid to the tank roof. If the sloshing caused by earthquake exceeds from the tank freeboard, the liquid may collides to the tank roof and induces an extensive hydrodynamic force on it. This liquid impact forces were also considered by Goudarzi et al. [12]. Due to these adverse effects of the sloshing, the reduction of sloshing wave height caused by the seismic excitations is one of the major concerns in the seismic analysis of liquid storage tanks.

To encounter the violent sloshing, especially under near-resonant excitation, the baffles are generally employed in various industries. To increase the damping ratio, and decrease the slosh forces, the baffles are effective internal components, especially due to their simple installation and high performance. The shape and position of the baffles depend on the type of sloshing motion, container shape and the kind of external excitation [4]. The effects of the baffles configuration on the performance of the service

* Corresponding author: Tel.: +98 21 22830830; fax: +98 21 22299479.
E-mail address: m.a.goodarzi@iiees.ac.ir (M.A. Goudarzi).

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reservoir show that the baffles break up the vortex to shorten the flow path. Besides, the velocity magnitude of the fluid is reduced after flowing past throw the baffles [24].

There are several studies carried out on different aspects of sloshing suppression using the baffle since mid 50 s. Miles [20] is one of the primary researchers that analytically investigate the damping effects caused by the baffles. One of the headmost references in this issue is a NASA report presented by Abramson and Silverman [1]. Maleki and Ziyaeifar [18] also developed an analytical solution using Laplace's differential equation for estimating the damping ratio of liquid sloshing in baffled tanks undergoing horizontal excitation. The method involved the assessment of dissipated fraction of total sloshing oscillation energy caused by the flow separation around the baffles. They also considered the effectiveness of baffles for seismically isolated cylindrical liquid storage tanks [19].

Wall bounded baffles were generally placed vertically or horizontally inside a liquid storage tank. The vertical type baffles can be Upper Mounted Baffles (UMB) which intersect the free surface or lowest mounted baffles which were positioned at the bottom of a tank. While, the horizontal baffles type placed vertical to a tank sidewalls. The horizontal baffles as well as bottom mounted vertical baffles were analytically and experimentally studied by the authors in their previous investigation [11]. They were established an analytical solution approach and experimental investigations for describing the hydrodynamic damping provided by vertical and horizontal baffles in partially filled rectangular tanks. The authors also considered the effectiveness of UMB inside a rectangular tank [13].

In later paper, experimental and analytical evaluations of the hydrodynamic damping due to UMB were conducted. Moreover, the comparison between maximum hydrodynamic damping caused by various baffle configurations was made and it was concluded that the UMB can be more effective than bottom mounted baffles. Therefore, the UMB may be able to be used in practical seismic engineering of liquid storage tanks. However, the ability of developed analytical solution to properly evaluate the damping effects of UMB in real world tanks, as well as, the effectiveness of this baffle type for sloshing suppression demands separate investigation. These issues are the primary objectives of the present study. For this purpose, the numerical method was employed for modeling the full scale tanks under earthquake excitation.

Numerical methods have been extensively employed to predict the sloshing behavior in liquid containers. From numerical point of view, fluid sloshing problems are generally described by the governing equations, in terms of the Navier–Stokes equations, and boundary conditions including dynamic and kinematic conditions of free surface and the velocity conditions on the walls. The numerical methods are frequently employed due to the complication of fluid flow pattern around the baffles [17,22].

A boundary element method is one of the numerical methods used to model the liquid sloshing. Faltinsen [9] is one of the primary researchers who developed the boundary element method model to solve sloshing problems. The other type of boundary element method was also applied to study the effects of baffle arrangements with arbitrary geometries [6]. It was shown that the variation of sloshing and structural dynamics frequencies versus baffle flexibility is a function of the direction of both sloshing vibration mode shapes. Ebrahimian et al. [7] also employed boundary element model to determine sloshing natural frequencies of symmetric and axisymmetric modes of a multi-baffled tanks.

A finite element method is another numerical method widely used to numerical modeling of the baffled tanks. Cho et al. [5] used this method to investigate the resonance characteristics of liquid sloshing in a baffled tank subjected to the forced lateral excitation. They studied the sloshing damping characteristics by the baffle to consider the number, location and opening baffle width. The finite difference scheme with fictitious cell technique was also used to study viscous fluid sloshing in two dimensional tanks with baffles [23].In this study, the effects of baffles on the sloshing displacement were considered and the influence of baffle height on shifting of the first natural mode of baffled tank under different water depths was carried out.

A volume of fluid method is the most commonly used numerical method to capture the fluid motion especially when the internal baffles are used. The volume of fluid method technique with arbitrary-Lagrangian–Eulerian formulation was employed for obtaining the effect of baffles on liquid sloshing for a partially filled cubic tank [8]. The volume of fluid method in three dimensional space was also used to study the effect of the vertical baffle height on the liquid sloshing in a laterally moving three-dimensional rectangular tank [16]. This study showed that the vortex generated by the flow separation from the baffle tip becomes weaker and smaller with increasing baffle height.

Another numerical algorithm based on the volume of fluid technique was established by Akyildiz [2] in which the variation of hydrodynamic damping of the baffle including the blockage effects and the viscosity of baffle wall due to the variation of the baffle height was studied [2].

In the present paper, the hydrodynamic damping effects of the Upper Mounted Baffles (UMB) which is placed inside the full scale liquid tanks are numerically investigated. As mentioned before, primary objective of this study is to examine the accuracy of the analytical solution previously developed by one of the authors [13,14] for prediction of UMB hydrodynamic damping in real scale liquid tanks. This analytical solution has been already validated by the experimental measurements in small scale tanks. However, its accuracy for the full scale tanks under seismic excitation is considered in present paper.

For this purpose, the finite volume method is used to analyze several tanks equipped by UMB with various aspects ratios. The reduction of the maximum sloshing wave height (MSWH) due to the presence of the UMB is investigated under earthquake excitations. The MSWH is practically required for seismic design of the liquid tanks. Therefore, second purpose of the paper is to suggest the proper seismic design procedure to estimate the UMB effects on the suppression of MSWH in liquid tanks. The proposed method can be used by the designer to primary evolution of the MSWH reduction due to the presence of UMB. The predictions of proposed method are compared with the results of numerical analysis for considered tanks.

2. Analytical evaluation of the UMB damping effect

In general, damping ratio could be defined as the ratio of energy dissipation rate and total energy of a system in special time interval. Therefore, damping ratio (ξ), regardless of its source, can be estimated by well-known energy-ratio formula mentioned below [21,15]:

$$\xi = \frac{1}{\omega} \frac{\mathrm{d}E/\mathrm{d}t}{E} \tag{1}$$

Above relation could be used to estimate the damping ratio of various systems.

In order to analytically evaluate the damping ratio provided by UMB, the liquid velocity during the liquid sloshing is required. Based on the assumption that the liquid velocity field in liquid domain is not considerably changed by the presence of baffles, the analytical velocity distribution of un-baffled tank can be used to calculate the damping caused by the baffles.

The details of suggested analytical model developed to predicting the damping effects of the various types of baffle have been