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Mechanical model for cylindrical flexible concrete tanks undergoing lateral excitation

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ABSTRACT

In this paper, a mechanical model is developed for evaluating the seismic response of flexible concrete cylindrical tanks under horizontal ground motion. For obtaining the parameters of the liquid-shell interaction of this model, a semi-analytical approach is employed using the Rayleigh–Ritz method. In the developed analytical approach, the vibration modes of a deformable open-top clamped-bottom shell are considered. The shell is assumed to be thin and the first-approximation theory is applied. Based on the analytical approach, a simple yet sufficiently accurate mechanical model, in which effects of the liquid and the tank wall considered separately, is proposed for tanks completely or partially filled with liquid. Parameters of this model are illustrated in charts easy to use for design purposes. In this model, only the first circumferential and vertical modes are considered. Also, the time history of sloshing wave height and its maximum are obtained. Finally, the base shear and the overturning moment, calculated by the analytical method and proposed mechanical model, are compared with those suggested by ACI 350.3-06. The results demonstrate that the proposed mechanical model is very successful in predicting the base shear and overturning moment, but ACI 350.3-06 overestimates or underestimates the responses case by case. Therefore, this model can be utilized with confidence for estimation of the design seismic loads of concrete cylindrical tanks.

1. Introduction

Liquid storage tanks, as special structures, behave differently from ordinary structures in terms of dynamic characteristics. These important structures are mostly constructed in two different shapes of cylindrical and rectangular in accordance with their use for storing various liquids such as water and oil in the form of ground, elevated, buried and semi-buried structures. Due to the large forces caused by the hydrodynamic pressure during ground motion, the correct evaluation of these containers is very important.

One of the first investigations on a rigid tank under earthquake excitation was that of Hoskins and Jacobsen [1]. Although investigation of the dynamic responses of a liquid storage tank was started based on the study of the dynamic responses of a fuel tank in aerospace engineering [2] and there are some research in mechanical engineering about it [3,4], there is a difference between the research on the dynamic responses of fuel tanks in aerospace or mechanical engineering and those in civil engineering. The latter is more concerned with response in the lower frequencies as the size of such tanks is so large. Consequently, the dynamic response resulting from the lower frequencies dominates the critical stresses and deformation of the tanks used in civil engineering practice [5].

Housner [6,7] developed a mechanical model based on a simplified analytical method for evaluating the hydrodynamic actions of a rigid cylindrical tank. This model consisted of two lamped masses, one for the impulsive and the other for the convective action. The mentioned model made the first basis for design of the cylindrical tanks with a rigid wall assumption. After the large-scale damage of 1964 great Alaska earthquake, Hanson [8] published a detailed report about the behavior of liquid storage tanks under this earthquake. After that, the importance of flexibility of tank wall was endorsed by many researchers.

Veletsos and Yang [9] estimated the impulsive seismic load of flexible tanks by using a similar rigid tank assumption with modification. Instead of calculating the maximum acceleration for the rigid tank, they used the spectral acceleration associated with the natural frequency of the liquid-shell system for a similar deformable tank. They presented a simplified formula to obtain the fundamental natural frequency of the steel liquid-filled cylindrical tank. They paid special attention to the first symmetrical circumferential vibration mode. They

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concluded that the impulsive pressure distribution was similar for rigid and flexible tanks. However, the magnitude of hydrodynamic pressure depended on the flexibility of the tank wall.

Balendra and Nash [10] modeled the steel cylindrical tanks using thin shell elements and analyzed them by the finite element method. They ignored the effect of sloshing and simplified the cylindrical fluid container by considering an empty shell with an added mass representing the liquid inside it.

Haroun and Housner [11,12] presented a method for the dynamic analysis of steel cylindrical tanks full of liquid, using the finite element method. The impulsive and convective hydrodynamic pressures were expressed by the potential flow approach. Based on this research, they developed a three-degree-of-freedom model for the ground-supported flexible cylindrical tanks. The application of which resulted in design charts used to estimate sloshing and impulsive components and amount of the rigid mass. For evaluating the effective masses, only the fundamental natural mode of vibration of the deformable tank was considered. Their model disregarded the effect of the tank wall weight. Also, it does not have the ability to analyze partially filled tanks.

Veletsos and Tang [13] presented an analytical solution for the Laplace equation governing the fluid for rigid cylindrical tanks subjected to a rocking base motion. They introduced a modified model in which the effect of higher sloshing modes was considered. They obtained the approximate impulsive hydrodynamic pressure on the deformable cylindrical tanks based on the formula for similar rigid tanks.

Malhotra et al. [14] used the model of Veletsos et al. [9] and offered a simple model for cylindrical tanks under horizontal excitation. In their model, the effects of higher impulsive and convective modes of vibrations were considered. Shahverdiani et al. [15] investigated the behavior of concrete cylindrical tanks under harmonic excitation using the finite element method with ANSYS. They considered wall flexibility, liquid sloshing and viscosity in their study.

In another study, Moslemi and Kianoush [16] investigated the behavior of concrete cylindrical tanks under horizontal ground motion using the finite element method by ANSYS. The obtained results were compared with those using ACI 350.3-06 for estimating the seismic response of liquid in cylindrical containers. Finally, they concluded that the seismic loads in this standard were estimated much larger than those obtained by the finite element model. Hashemi et al. [17,18] implemented the Rayleigh–Ritz method to present a semi-analytical method for the behavior of rectangular liquid storage tanks undergoing horizontal excitation. In their research, the flexibility of tank walls was considered. Then, based on their analytical method, a mechanical model for estimating the seismic loads was developed.

The results of the aforementioned studies conducted by Moslemi and Kianoush [16] and Hashemi et al. [17,18] have shown that impulsive seismic responses such as base shear, overturning moment and distribution of the hydrodynamic pressure proposed by ACI 350.3-06 [19] are not in good agreement with numerical procedures and a lot of difference is observed in estimating the seismic responses. This drawback mainly originates from the mechanical model that is exploited in this standard. Generally, the well-known codes used for the design of cylindrical storage tanks [19–21] utilize Housner's model with the rigid wall assumption [6,7] for flexible tanks with some modification. Therefore, it is necessary to propose a mechanical model to modify the existing insufficiencies.

In the present study, the Laplace equation governing the behavior of fluid in tanks is divided into two parts, namely impulsive and convective responses. To evaluate the impulsive responses on the fully or partially filled flexible containers, the liquid-shell interaction effects are considered. The convective response can be determined assuming a similar rigid tank, with minimal loss of accuracy [22]. In this study, therefore, the Rayleigh-Ritz method is employed for analysis of the liquid-shell system. It should be noted that the main focus is placed on the impulsive seismic response because most of the insufficiencies are in this action. Therefore, in the first part of this paper, a more accurate analytical method is developed to evaluate the liquid-shell interaction effects of partially filled concrete cylindrical tanks with flexible walls undergoing horizontal excitation. To obtain the impulsive pressure, the Rayleigh-Ritz method is applied, using the vibration modes of open top-clamped bottom shells and $n \geq 1$ for the $Cos\ n\theta$ circumferential modes.

In the second part of this paper, a simple and accurate mechanical model is proposed by means of a response spectrum for estimating the seismic responses of concrete cylindrical tanks, in order to modify current insufficiencies of ACI 350.3 [19]. The parameters of this model are obtained based on the proposed analytical method from the developed charts and the case of a partially filled tank is also included. This aspect is not commonly accounted for in the related structural codes. Furthermore, the effects of both wall flexibility and inertia are considered in the presented analytical procedure and the proposed mechanical model. It is worth mentioning that, although the wall mass has a great importance in the seismic response of the concrete storage tanks, common codes only superficially considered its role. The time history of the sloshing wave height and its maximum is obtained with reasonable accuracy based on the convective pressure of a similar rigid tank [22].

2. Fundamental equations

The storage tank under consideration is a cylindrical tank with a deformable wall of uniform thickness t_w, open top ground-supported with a horizontal rigid bottom that is partially filled with liquid of height H_L. The interior radius and height of the tank are R and H_S respectively. The liquid is incompressible and non-viscous (like water and petroleum) and the wall of the tank is considered as a thin shell made of linearly elastic, homogeneous and isotropic material.

Fig. 1 shows the cylindrical coordinate system. In this figure, the radial, circumferential and axial coordinates are denoted by r, θ and z, respectively and the corresponding displacements of a point on the middle surface of shell are denoted by w, v and u, respectively.

The motion of the liquid is assumed to be frictionless and irrotational. Such a simplifying assumption makes the liquid motion to be governed by the Laplace equation according to the theory of fluid dynamics [23], as:

$$\nabla^2\Phi = \frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\theta^2} + \frac{\partial^2\Phi}{\partial z^2} = 0 \tag{1}$$

in which Φ is the velocity potential function. The fluid velocity at an arbitrary point and time (t) in the direction of a generalized coordinate n, is [23]:

$$v_n = -\frac{\partial\Phi}{\partial n} \tag{2}$$

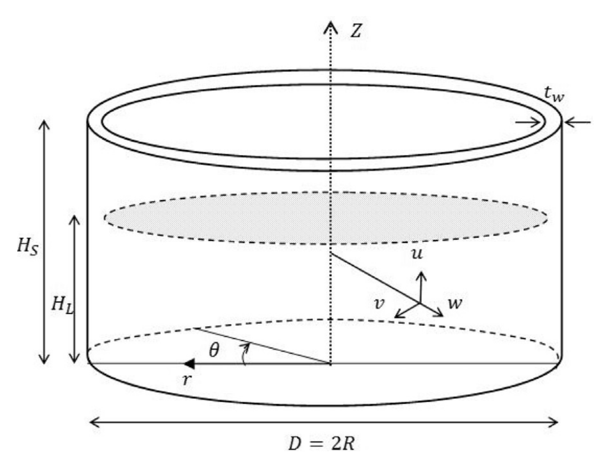

Fig. 1. Cylindrical tank and the coordinate system.

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