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Seismic responses of base-isolated flexible rectangular fluid containers under horizontal ground motion

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ABSTRACT

This paper focuses on analyzing, the results and arguments about the analysis of seismic base-isolated flexible rectangular containers. An equivalent mechanical model of rectangular containers with three lumped masses and six degrees of freedom is used. Lead rubber bearing (LRB) and friction pendulum system (FPS) are two types of seismic isolators, used to isolate the storage tank base. Results show that seismic base isolation can be an efficient way to reduce seismic responses such as base shear, wall deflection and hydrodynamic pressure, but it can adversely affect the free surface sloshing height. The seismic responses of isolated tanks under unidirectional excitation (No interaction) and bidirectional excitation (Interaction) are not considerably different and the results are not very sensitive to the interaction effect of the bearing forces. In any case, the careful choice of the number and the mechanical characteristics of seismic base isolation systems is suggested to achieve good responses.

1. Introduction

Liquid storage containers are one of the most important structures of lifeline and industrial facilities in the world. These structures can be configured as ground-supported, elevated and partly buried and may be made of concrete or steel. The ground-supported concrete rectangular containers are widely used for the long-term storage of nuclear spent fuel assemblies and certainly they are exposed to a wide range of seismic hazards and interaction with other sectors of the built environment. The poor performance of some of these structures in past earthquakes has led engineers and researchers to study this problem, and to improve the behavior of them.

Haskins and Jacobsen [1] published the first report on analytical and experimental observation of rigid rectangular tanks under a simulated horizontal earthquake excitation. Housner [2] developed the most commonly used analytical model for estimating the dynamic response of a rigid rectangular tank. This model, with some modifications, has been adopted in most of the current codes and standards. Haroun [3] presented a very detailed method of analysis of the typical system of loadings for rectangular tanks, but the formula of hydrodynamic pressures only considered the rigid wall condition.

Several studies were carried out to investigate the dynamic interaction between the deformable wall of the tank and liquid in it. Kim et al. [4] presented an analytical method for calculation of hydrodynamic pressures based on the three-dimensional analysis of tanks. Dogangun et al. [5] and Dogangun and Livaoglu [6] investigated the seismic response of liquid-filled rectangular storage tanks using the three-dimensional Lagrangian fluid finite element. Koh et al. [7] studied the seismic response of rectangular tanks with four flexible walls by using a three-dimensional coupled boundary element-finite element method. Ghaemmaghami and Kianoush [8] investigated the behavior of concrete rectangular tanks using the FEM in 2D space. Chen and Kianoush [9] proposed a simplified method, using the generalized SDOF system to study the dynamic response of liquid storage tanks. Hashemi et al. [10] investigated the dynamic response of flexible 3D rectangular liquid storage tanks with flexible walls on all four sides, subjected to horizontal seismic ground motion. In most common standards and codes currently used for the design of tanks, the importance of the effects of wall flexibility has been recognized and the corresponding increase in the acceleration coefficients has been adopted [10].

Based on observation from the mentioned researches, it is concluded that: (i) liquid storage tanks can be subjected to large seismic forces such as base shear and hydrodynamic pressures during earthquakes, (ii) the seismic response of liquid storage tanks can be strongly influenced by the interaction between the wall flexibility and the fluid within it and (iii) the seismic response of a flexible tank may be substantially greater than that of a similar rigid tank. Hence, protection of these structures against hydrodynamic pressures which increase by severe

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seismic events has become crucial.

One of the popular methods for protecting liquid storage tanks is base isolation systems. The employment of a seismic isolation system imposes additional costs of bearings, hardened base slab and flexible pipe connections and may increase the initial construction cost. On the other hand, the probability of damage and the expected damage cost due to earthquake events can be reduced by a significant amount. Therefore, cost-effectiveness evaluation for the seismically isolated structure will help designers to make decisions on the use of the isolation system. Bo and Jia-Xiang [11] studied the seismic response of base-isolated cylindrical liquid storage tanks under earthquake loading and observed that LRB systems can greatly reduce the hydrodynamic pressure. Kim and Lee [12] experimentally investigated the seismic performance of cylindrical liquid storage tanks isolated by LRB under unidirectional excitation and showed that the isolation is effective in reducing dynamic responses. Shrimali and Jangid [13] investigated the non-linear seismic response of cylindrical tanks isolated by LRB under bi-directional earthquake excitation and observed that the base isolation system is quite effective in reducing seismic responses of the liquid storage tanks. Chalhoub and Kelly [14] observed that due to the reduction in the ground accelerations by isolation systems, the hydrodynamic pressure is reduced for the tank but free surface water elevation is slightly increased because of the lower frequency that characterized the motion of base-isolated structures. Malhotra [15] investigated the seismic response of base isolated steel tanks and found that isolation systems were beneficial in reducing the response of the tanks without any significant change in sloshing displacement. Jadhav and Jangid [16] investigated the Seismic response of the liquid storage tanks isolated by the elastomeric bearings and sliding systems under near-fault earthquake motions.

There are also a number of researchers who have studied the effectiveness of the seismic isolation technique for elevated tanks. Shenton and Hampton [17] and Moslemi [18] studied the seismic response of isolated elevated tanks and found that seismic isolation is effective in reducing the tower drift, base shear, overturning moment and tank wall pressure for the full range of tank capacities. Mori et al. [19] studied two heritage-listed elevated cylindrical liquid storage tanks in which the storage tank had been modeled by finite element and equivalent mathematical models and the effectiveness of isolation systems on the responses was considered.

Furthermore, the soil-structure-isolator interaction effects for the base-isolated cylindrical tanks were investigated. Cho et al. [20] studied a coupled dynamic system in which the base isolation system and the soil-structure interaction effects were considered. They offered a general numerical algorithm that can be used to analyze the base-isolated liquid storage tanks. The base isolation system was modeled using the biaxial hysteretic element in their study.

Generally, last investigation shows that seismic isolation is an effective alternative for reducing the vibration amplitude of structures under seismic waves. However, the studies are limited principally to cylindrical tanks and investigations in the literature regarding the application of this technique to flexible rectangular fluid containers are extremely rare. Park et al. [21] introduced a method for estimating the cost-effectiveness of seismically-isolated pool structures. In the numerical examples, they found that seismic isolation is more cost-effective in a region of low-to-moderate seismicity than in a region of high seismicity. The results also showed that the effectiveness is more pronounced in a stiffer soil condition. Park et al. [22] investigated the dynamic behavior of the pool-type rectangular concrete structures with a HDR base isolation system for the storage of nuclear spent fuel assemblies, considering the effects of the fluid-structures interaction.

In the present study, seismic analysis of flexible rectangular fluid containers isolated by two other kinds of base isolators containing Lead Rubber Bearings (LRB) and Friction Pendulum Systems (FPS) are investigated under horizontal seismic ground motion. In order to measure the effectiveness of the isolation systems, the earthquake response of isolated tanks is also compared with fixed-base containers subjected to bi-directional excitation.

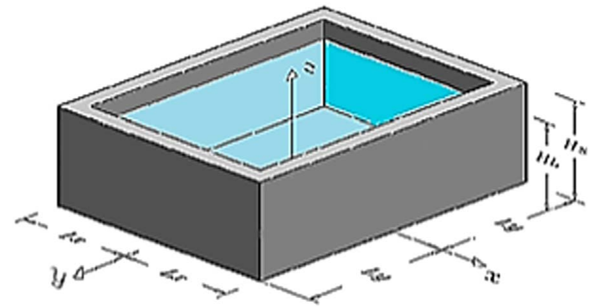

Fig. 1. 3D model of rectangular tank.

2. Mechanical model

The 3D Finite Element Model (FEM) of base isolated liquid storage tank is extremely complicated [23]. Comparison results of a FEM and an equivalent simplified mechanical model showed that the mechanical model can be used with confidence for the preliminary analysis of base-isolated tanks [24]. Therefore, in present study simplified models are used for preliminary analysis of flexible rectangular containers.

The considered mechanical model is based on the model previously developed by one of the co-authors of this paper (Hashemi et al.[10]). The model includes a spring-mass model in which the effect of flexibility of the tank is considered. They used a rectangular tank with four flexible vertical walls of uniform thickness, t_s, and a horizontal rigid bottom partially filled with incompressible and non-viscose liquid depth, H_l, to provide the mechanical model (Fig. 1). The side lengths and height of this structure are $2L_x$, $2L_y$ and H_s, respectively. Fig. 2 shows mechanical model of a rectangular liquid storage tank supported on a typical isolation system.

The contained continuous liquid mass is lumped as convective, flexible and basic masses referred to as m_c, m_f and m_0, respectively. The convective and flexible masses are connected to the tank wall by springs having circular natural frequencies and damping ratios of ω_c, ω_f, ξ_c and ξ_f, respectively. The equivalent mechanical model has six degrees of freedom under bi-directional earthquake ground motion, two degrees of freedom of each lumped mass in two horizontal x- and y-directions. These degrees of freedom are denoted by (u_{cx}, u_{cy}), (u_{fx}, u_{fy}) and (u_{0x}, u_{0y}) which show the absolute displacement of convective, flexible and

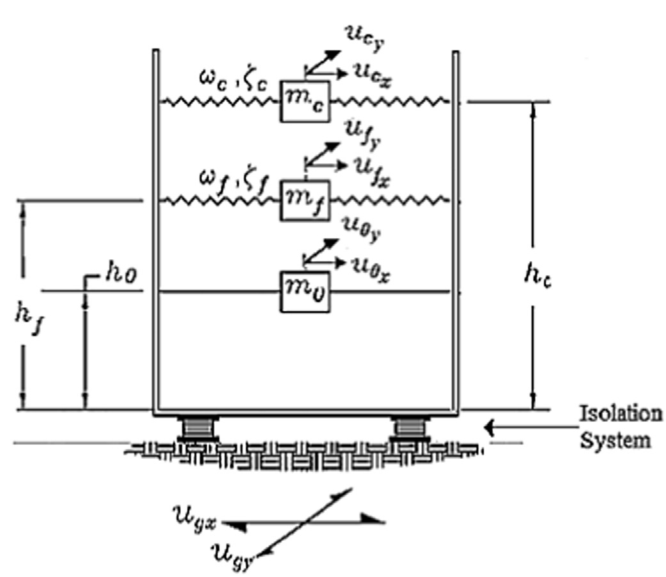

Fig. 2. Mechanical model of base-isolated flexible tank.