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Seismic performance assessment of FPS isolated liquid storage tanks at various intensity levels

Saman Bagheri[1], Hossein Hayati Raad[2]

[1] Associate Professor, Faculty of Civil Eng., University of Tabriz, Tabriz, Iran
[2] Graduate Student, , Faculty of Civil Eng., University of Tabriz, Tabriz, Iran

ABSTRACT: On-grade steel tanks are widely used to store liquids, such as oil or other petroleum products. The inappropriate behavior of these industrial facilities which frequently resulted in serious structural or nonstructural damages, have been reported in some recent earthquakes. Seismic base isolation is one of the most efficient techniques to mitigate earthquake damage in both new and existing liquid storage tanks. This paper deals with the seismic performance and damage assessment of on-grade liquid storage tanks isolated by the friction pendulum system (FPS). As a sliding type isolation system, FPS introduces nonlinearity into the dynamic analysis of the model, leading to likely different performances at various levels of input excitation. To estimate the seismic demands for different levels of intensity, incremental dynamic analysis (IDA) under a suit of strong ground motion records is carried out. The effects of tank aspect ratio, isolation period and friction coefficient on the seismic response of isolated tanks are investigated and the obtained results are compared with those from fixed ones.

KEYWORDS: Storage tank, earthquake, base isolation, incremental dynamic analysis.

1 INTRODUCTION

Liquid storage tanks are one of the most important industrial structures that their dynamic behavior is different from other structures such as buildings and bridges because of the hydrodynamic forces of the contained liquid. The observations of some typical damages to on-grade steel tanks during past earthquakes have repeatedly demonstrated their inappropriate performances (Cooper, 1997; Hamdan, 2000). Some techniques to reduce the damages in these structures have been examined by several researchers. One of these techniques is to use base isolators. As a first attempt to study this subject experimentally, Chalhoub and Kelly (1990) conducted shake table tests of fixed-base and base isolated cylindrical steel tanks. They observed that as a result of isolation, the dynamic pressures were reduced considerably with a slight increase in sloshing motion of the liquid.

Malhotra (1997) proposed a new method for seismic base isolation of on-grade cylindrical liquid storage tanks by disconnecting the wall of the tank from the base plate and showed that the overturning moments and axial compressive stresses in the tank wall could be reduced significantly. The feasibility of using FPS bearings for seismic base isolation of rigid cylindrical storage tanks was explored by Wang et al. (2001). The effectiveness of this sliding-type isolation system was verified through numerical simulations under the 1940 El Centro earthquake. A comparative study of performance of various isolation systems for on-grade storage tanks by Shrimali and Jangid (2002) also confirmed that the sliding-type isolation systems were more effective in controlling the seismic response of the tanks in comparison with the elastomeric bearings. Moreover, the seismic behavior of elevated liquid storage tanks isolated by high damping rubber bearings and friction pendulum isolators was analyzed and compared by Paolacci (2015). Bagheri and Farajian (2016) investigated the nonlinear dynamic behavior of FPS isolated liquid storage tanks under ground motion with different characteristics and observed that the FPS was more effective in reducing the seismic responses under far-field ground motions compared to near-fault ground motions.

As a sliding-type isolation system with velocity-dependent friction law, FPS introduces nonlinearity into the dynamics of the system which can result in different performances at various levels of input excitation. To account for this, incremental dynamic analysis (IDA), that was initially developed for frame structures (Vamvatsikos and Cornell, 2002), can be extended to our case. In this procedure, a series of nonlinear dynamic analyses of a structural model under an ensemble of ground motion records, each scaled to several levels of intensity, is performed. In the present work, the seismic responses of the FPS isolated liquid storage tanks are obtained from the IDA procedure and compared with those of fixed-base ones at various levels of input intensity. Also, the influences of tank aspect ratio, isolation period and friction coefficient on the performance of the isolated tanks are studied at various intensity levels.

2 MODELING

2.1 *Mathematical model of the isolated liquid storage tank*

Housner (1963) proposed a simple approximate mechanical model to estimate the dynamic effects of liquid in a ground supported tank with rigid wall and incompressible fluid under the horizontal seismic excitation. The model was then improved by Haroun and Housner (1981) to take into account the flexibility of the tank wall. In such mechanical models the liquid mass is divided into two parts: the impulsive component that moves in unison with the tank wall near the base of the tank, and the convective component that experiences sloshing motion near the free-surface. Later on, Malhotra et al. (2000) proposed a simple, yet accurate, and more generally applicable equivalent mechanical model of the tank-liquid system by combining the higher impulsive modal mass with the first impulsive mode and the higher convective modal mass with the first convective mode.

The mathematical model used in the present study is the latter which is resting on a base isolation system as shown in Figure 1. The geometrical parameters of the tank are the liquid height (H), radius of the tank (R), and the equivalent uniform thickness of the tank wall (t). The convective and impulsive masses (m_c and m_i) are connected to the tank wall by springs having stiffnesses of k_c and k_i, respectively. The damping coefficients of the convective and impulsive masses are denoted as c_c and c_i, respectively. The calculation method of these parameters has been described in detail by Malhotra et al. (2000).

2.2 *Governing equations of motion*

A three-degree of freedom system of a base isolated liquid storage tank is shown in Figure 2. The equations of motion can be written as:

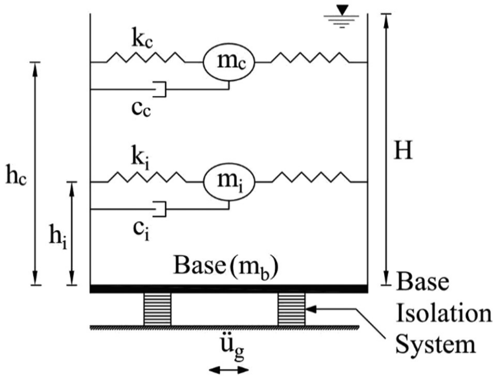

Figure 1. Mathematical model of a base isolated liquid storage tank used in this study

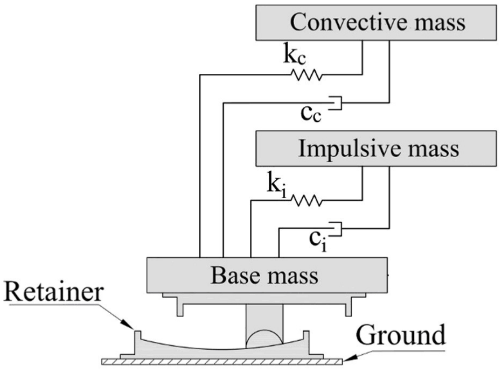

Figure 2. Three-degree of freedom system of a base isolated liquid storage tank

$$m_c\ddot{u}_c + c_c(\dot{u}_c - \dot{u}_b) + k_c(u_c - u_b) = -m_c\ddot{u}_g \tag{1}$$

$$m_i\ddot{u}_i + c_i(\dot{u}_i - \dot{u}_b) + k_i(u_i - u_b) = -m_i\ddot{u}_g \tag{2}$$

$$m_b\ddot{u}_b - k_c(u_c - u_b) - k_i(u_i - u_b) - c_c(\dot{u}_c - \dot{u}_b) - c_i(\dot{u}_i - \dot{u}_b) + F = -m_b\ddot{u}_g \tag{3}$$

where u_c, u_i, and u_b are displacements relative to the ground for the convective, impulsive, and base masses respectively; $\ddot{u}_g$ is the earthquake ground acceleration; m_b is the base mass; and F is the horizontal force exerted by FPS. This force and the isolation period, T_b, are given as:

$$F = \frac{W}{R_b}u_b + \mu W \,\mathrm{sgn}(\dot{u}_b) \tag{4}$$

$$T_b = 2\pi\sqrt{\frac{R_b}{g}} \tag{5}$$

where W is the vertical load on the isolator produced by the total weight of the system, i.e. $(m_c+m_i+m_b)g$, R_b is the radius of curvature of the sliding surface, and μ is the velocity-dependent coefficient of friction governed by Eq. (6). In the aforementioned force of Eq. (4), the first term is the linear elastic spring force with its stiffness based on the curvature of the spherical dish and the second term is the friction force. In the latter term, a continuous hysteretic variable ranging between -1 and 1 governed by the modified Bouc-Wen model can replace the sign function to avoid difficulties in the numerical solution of the equations (Fenz and Constantinou, 2008). The velocity-dependent coefficient of friction is given as:

$$\mu = \mu_{\max} - (\mu_{\max} - \mu_{\min})\exp(-a|\dot{u}_b|) \tag{6}$$

where $\mathring{u}_b$ is the sliding velocity, μ_{max} and μ_{min} are the sliding coefficients of friction at large velocity and nearly zero sliding velocity, respectively, and a is a rate parameter that controls the variation of friction coefficient. a=100 s/m is often used for the type of material commonly used in FPS bearings (Fenz and Constantinou, 2008).

The governing equations of motion are solved using the state-space method by a provided MATLAB routine. The numerical results will be presented in terms of the overturning moment (M) and vertical displacement of the liquid surface due to the sloshing motion (d_v) according to Eqs. (7) and (8), respectively (Malhotra, 1997). The overturning moment directly indicate the seismic demand on the tank, which may lead to the buckling of the tank wall, possible damage to the bottom plate, and rupture of connections. On the other hand, the free surface displacement reflects the need for a sufficient freeboard and can be considered in relation to damage of the roof or top wall and spill of the contents over the tank.

$$M = -\{m_c h_c(\ddot{u}_c + \ddot{u}_g) + m_i h_i(\ddot{u}_i + \ddot{u}_g)\} \tag{7}$$

$$d_v = 0.837R\frac{\omega_c^2(u_c - u_b)}{g} \tag{8}$$

2.3 *Tank properties*

Two cylindrical steel tanks with different aspect ratios, one broad and one slender, have been used for numerical studies. The main properties of these tanks are summarized in Table 1, in which ρ indicates the mass density of the contained liquid (water) and E is the modulus of elasticity of the tank material (steel). The damping ratios for convective and impulsive masses are taken as 0.5% and 2%, respectively, as suggested previously for on-grade steel storage tanks (Haroun and Housner, 1981; Malhotra, 1997; Malhotra et al, 2000).

Table 1. Properties of the considered broad and slender tanks

Tank type	H (m)	R (m)	H/R	t (m)	E (GPa)	ρ (kg/m^3)
Broad	14.6	24.4	0.6	0.0203	200	1000
Slender	11.3	6.1	1.85	0.0058	200	1000

3 SEISMIC ASSESSMENT PROCEDURE

The twenty-two ground motion records in the far-field record set of FEMA P695 (2009) are adopted herein for the incremental dynamic analysis (IDA). A series of nonlinear dynamic analyses of the tank models under the selected ground motion records is performed by scaling each record to several levels of intensity. In this study, peak ground acceleration (PGA) is chosen as the earthquake intensity measure in the IDA procedure.

In order to assess the performance of the seismic isolation system at various levels of intensity, a non-dimensional performance index is used according to Eq. (9) for each response parameter. Positive values of the performance index mean reduction in the seismic response due to the isolation while negative values indicate the increase in the response.

$$Performance\,Index = \frac{\text{fixed base tank response} - \text{isolated tank response}}{\text{fixed base tank response}} \tag{9}$$

4 RESULTS AND DISCUSSION

4.1 Effect of base isolation

The seismic performance of the isolation system at various intensities for the broad and slender tanks with $\mu_{max} = 0.06$, $\mu_{min} = 0.03$, and $T_b = 2$ s is shown in Figure 3. Results illustrated herein are median values of the selected earthquake ground motions.

It is observed that due to the isolation the overturning moment is considerably reduced in both the broad and slender tanks. As the earthquake intensity increases, performance index for the overturning moment increases until it reaches an almost constant value of about 80% for the broad tank or a little more for the slender tank. This happens when the peak ground acceleration as the seismic intensity measure reaches about 0.3 g.

It is also seen that unlike overturning moment, the vertical displacement of the liquid surface not only does not decrease significantly by isolation, but also increases slightly at some levels of earthquake intensity. Indeed, because of the long period nature of sloshing motions, aseismic base isolation, which increases the period of the system, does not have much effect on this response parameter.

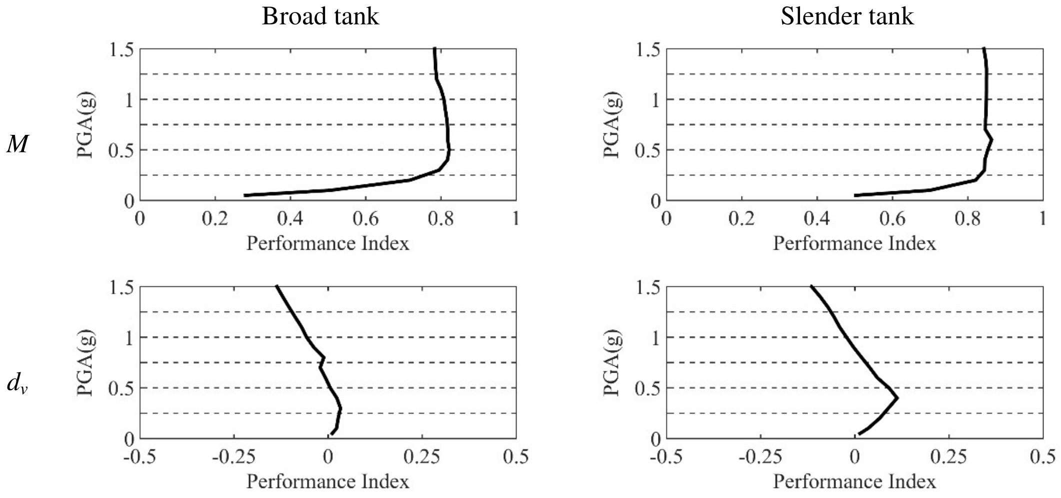

Figure 3. Seismic performance of the isolated tanks at various intensity levels

4.2 *Effect of isolation period*

In order to investigate the effect of isolation period on the seismic performance of the isolated tanks at various intensity levels, seven different isolation periods (T_b = 1, 1.5, 2, 2.5, 3, 4, 5 s) are considered for both broad and slender tanks. The friction coefficients are the same as in the previous subsection. The numerical results in the form of median IDA curves are shown in Figure 4.

The results indicate that reductions in the overturning moment due to base isolation of the tanks are almost identical for all assumed isolators until the PGA reaches about 0.2 g. After this stage, increase of the isolation period can increase the seismic performance of the system, but for isolation periods of more than about 3 s, the effect of this parameter is not significant. The figure also shows that different isolators can lead to a slight increase or decrease in the sloshing displacement at various intensity levels except those with high periods that decrease considerably this response parameter, especially at the high intensity levels.

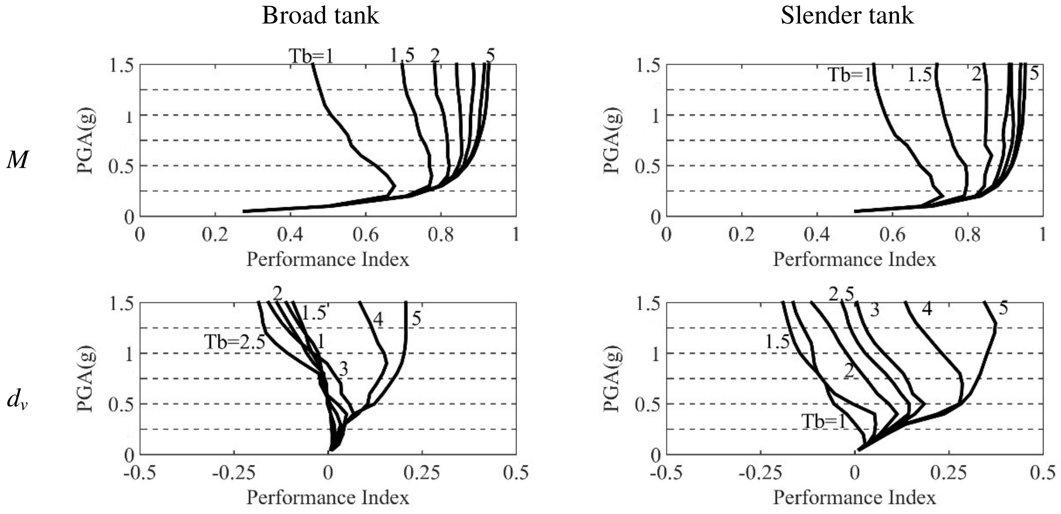

Figure 4. Effect of isolation period on the seismic performance of the isolated tanks at various intensity levels

4.3 *Effect of friction coefficient*

To investigate the effect of friction coefficient on the seismic performance of the isolated tanks at various intensity levels, μ_{max} has been varied from 0 to 0.12 and the value of μ_{min} has been assigned half of μ_{max}. The isolation period is the same as in the first subsection of this section. The obtained numerical results for the broad and slender tanks at various intensity levels are shown in Figure 5.

As is evident, under the frictionless condition, i.e. $\mu = 0$, the nonlinear behavior of the isolation system vanishes and the constant performance results for all input intensities. This condition has a considerable negative impact on the performance of FPS in reducing sloshing motions, but the effectiveness of the isolation system in reducing overturning moments remains as well. As the friction coefficient increases, the overturning moment increases in both broad and slender tanks in low intensity levels, which results in low performance of the isolator in reducing this response parameter. However, at high intensity levels, reductions in the overturning moment due to base isolation are almost identical for all assumed nonzero friction coefficients. On the other hand, in terms of vertical displacement of liquid surface, an increase in the friction coefficient can decrease and even eliminate the negative effect of isolation system, especially at high intensity levels.

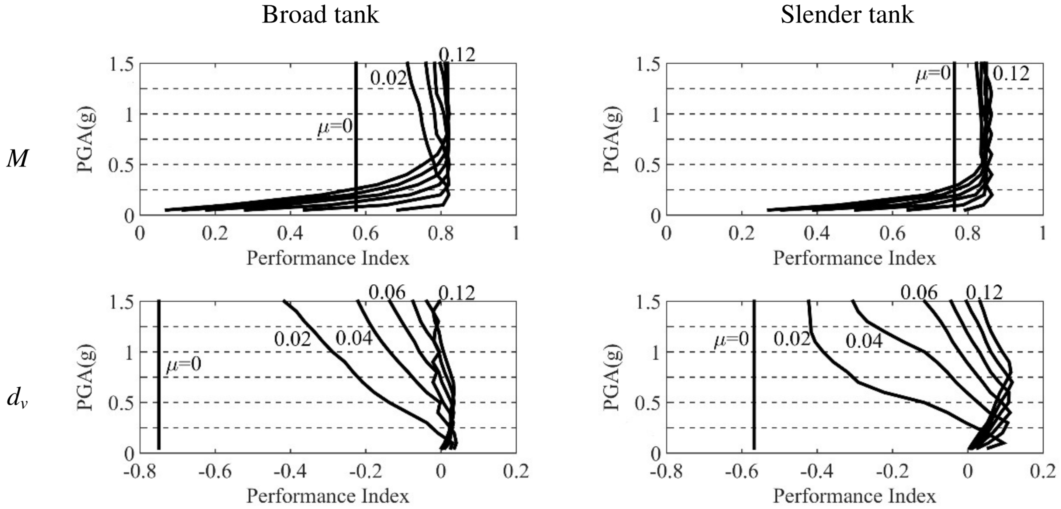

Figure 5. Effect of friction coefficient on the seismic performance of the isolated tanks at various intensity levels

5 CONCLUSIONS

This research was focused on the nonlinear behavior of FPS isolated storage tanks at various intensity levels of input ground motions. Following the estimation of seismic demands through incremental dynamic analysis, seismic performance assessment of isolated broad and slender tanks was performed at various intensity levels. It was observed that the Friction Pendulum System could be a quite effective isolation system in order to reduce the overturning moment as an indicator of structural damage in different levels of input excitation. However, the vertical displacement of the liquid surface due to the sloshing motion not only does not decrease significantly by the isolation system, but also increases at some levels of earthquake intensity. It was also seen that the isolation system had better performance in reducing overturning moments at high intensity levels. A number of different isolation periods and friction coefficients were finally examined at various intensity levels, and the associated effects on the seismic performance were discussed. In this regard, while the effect of isolation period on the seismic performance of the system was found to be more important at high intensity levels, the friction coefficient showed more effects on the overturning moment in low intensity levels.

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