16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 3350 (Abstract ID)
Registration Code: S-00015406

BEHAVIOR OF CONCRETE RECTANGULAR CONTAINERS ISOLATED USING DIFFERENT ISOLATION SYSTEMS SUBJECTED TO BI-DIRECTIONAL EXCITATION

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Abstract

This paper focuses on the comparison of the results of seismic response of concrete flexible rectangular containers isolated by three types of isolation systems. The considered isolation systems are high damping rubber-bearing (HDRB), lead-rubber bearing (LRB) and friction pendulum bearing (FPB). In order to measure the effectiveness of the isolation systems, the earthquake response of isolated containers is also compared with non-isolated tanks considering bi-directional excitation. An equivalent mechanical model of rectangular containers which has six degrees of freedom and contains three lumped masses known as basic mass, flexible mass and convective mass is used. Results of this study show that seismic base isolation can be an effective way to reduce seismic responses, such as base shear and hydrodynamic pressure. However, the inclusion of base isolators is found to increase the sloshing height. An increase in displacements for all isolation systems in horizontally isolated tanks seems to be inevitable. It is also found that the seismic response of isolated tanks is not very sensitive to the interaction effect of the bearing forces. A careful selection of isolators, with appropriate mechanical properties is needed for the optimal seismic isolation design of rectangular containers.

Keywords: rectangular containers, base isolation, seismic response, hydrodynamic pressure, bi-directional excitation

1. Introduction

Liquid storage containers are used extensively in lifeline and industrial facilities all over the world. These structures can be used as grounded, pneumatic and embedded containers. The grounded concrete containers are widely used such as those for the long-term storage of nuclear spent fuel assemblies. Hence, protection of these structures against severe seismic events has become crucial.

Recent research studies show that using seismic isolation systems under liquid storage tanks affects the seismic behavior of these structures. Chalhoub and Kelly [1] observed that the sloshing response increases slightly but the total hydrodynamic pressure decreases substantially due to the base isolation of the tanks. Kim and Lee [2] experimentally investigated the seismic performance of liquid storage tanks isolated by laminated rubber bearings under unidirectional excitation and have shown that the isolation is effective in reducing the dynamic response. Malhotra [3] investigated the seismic response of base isolated steel tanks and found that isolation was beneficial in reducing the response of the tanks over traditional fixed base tanks without any significant change in sloshing displacement. Shenton and Hampton [4] 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. Jadhav and Jangid [5] investigated the seismic response of liquid storage steel tanks isolated by elastomeric bearings and sliding systems under near-fault ground motions and found that both elastomeric and sliding systems were effective in reducing the earthquake forces of the liquid storage tanks. Panchal and Jangid [6] and Soni et al. [7] studied the behavior of cylindrical liquid storage tanks isolated by the variable friction pendulum isolator in which the liquid storage tank has been modeled by an equivalent mathematical model.

The above studies confirm that seismic isolation is effective in reducing the earthquake response and show that the fluid-structure-isolator interaction affects the response in cylindrical liquid storage tanks. However limited studies have been performed on rectangular liquid storage tanks with isolation systems. In addition, none of the studies have considered base-isolated concrete containers subjected to bi-directional excitation.

The present study focuses on a comparison of the results of seismic response of concrete flexible rectangular containers isolated by three types of isolation systems. The considered systems are high damping rubber-bearing (HDRB), lead-rubber bearing (LRB) and friction pendulum bearing (FPB). In order to measure the effectiveness of the isolation systems, the earthquake response of isolated containers is also compared with non-isolated tanks subjected to bi-directional excitation.

2. Mechanical model

Comparison results of a finite element model and an equivalent simplified mechanical model has shown that the mechanical model can be used with confidence for the analysis of base-isolated tanks with reasonable accuracy [8]. Therefore, in present study, simplified models are used for the analysis of concrete rectangular containers.

The considered mechanical model is based on the model previously developed by the co-authors of this paper (Hashemi et al. [9]). 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.

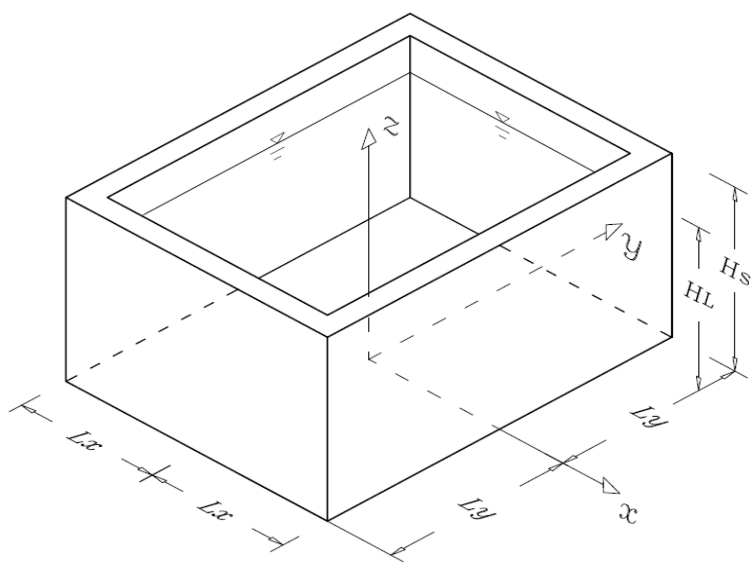


Fig. 1- 3D model of rectangular tank

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 basic masses in x- and y-directions, respectively.

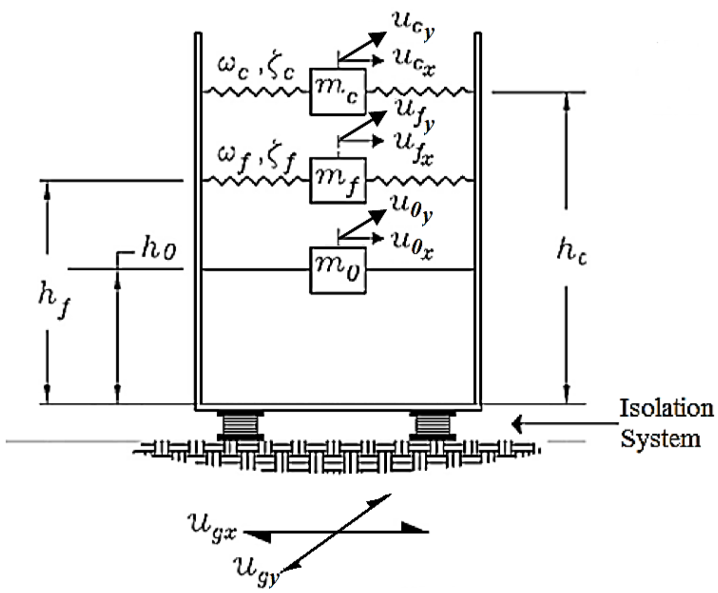


Fig. 2- Mechanical model of base-isolated flexible tank

The convective mass can be calculated according to the total mass of storage liquid (m_l) in a ratio defined as:

$$\frac{m_c}{m_l} = \frac{2\tanh(\mu\pi/2)}{\mu(\pi/2)^3} \tag{1}$$

$$m_l = 4L_x L_y H_l \rho_w \tag{2}$$

Where μ is a dimensionless parameter expressed as Eq. (3).

$$\mu = H_l / L_x \tag{3}$$

in which Lx is the half of side length in the direction which is studied. In determining the amount of m_r and m_f, equivalent masses corresponding to forces associated with ground motion and wall deformation relative to the ground, the effect of the liquid ($m_{r_{liquid}}$, $m_{f_{liquid}}$) and the wall ($m_{r_{wall}}$, $m_{f_{wall}}$) of the tank should be considered:

$$m_f = m_{f\ liquid} + m_{f\ wall} \tag{4}$$

And

$$m_0 = m_r - m_f \tag{5}$$

$m_{r_{wall}}$ is the total mass of the wall and foundation of the tank and $m_{r_{liquid}}$ is the total liquid mass that may be considered to be rigidly attached to the tank walls when they are considered as a rigid wall.

$$\frac{m_{r\ liquid}}{m_l} = 2\sum_{j=0}^{\infty} \frac{\mu}{\lambda_j^3} tanh\left(\frac{\lambda_j}{\mu}\right) \tag{6}$$

in which

$$\lambda_j = (2j+1)\pi / 2 \tag{7}$$

It should be mentioned that $(m_r)_{liquid}$ obtained using Eq. (6) is in good agreement with that determined by ACI 350.3 [24]. Hence, one can use Eq. (8) instead of Eq. (6).

$$\frac{m_r}{m_l} = \tanh(0.866/\mu)/(0.866/\mu) \tag{8}$$

for a tank completely filled with water, one can write:

$$\frac{m_{f\ liquid}}{m_l} = \tanh(1.732L_x / H_l) / \left(3.464L_x / H_l\right) \tag{9}$$

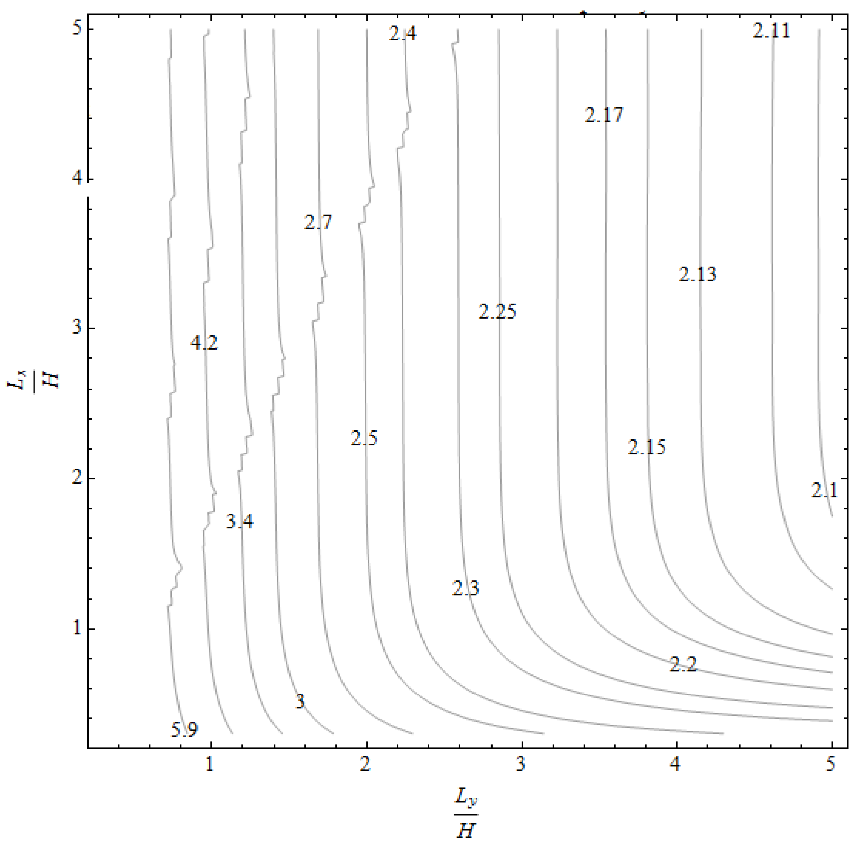
The fundamental natural frequency of convective mass, ω_c is given by the Eq. (10):

$$\omega_c^2 = g\,\alpha \tanh\left(\alpha H_l\right) \tag{10}$$

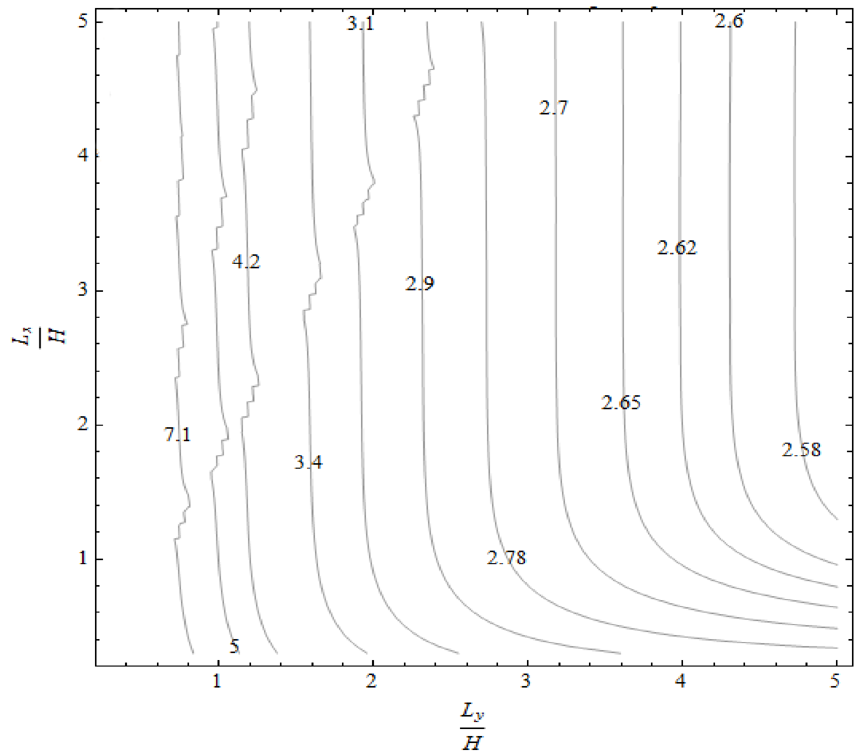
in which

$$\alpha = \pi / 2L \tag{11}$$

And g is the acceleration due to gravity.



(a)



(b)

Fig. 3. Dimensionless fundamental natural frequency (Ω_f) for tanks completely filled with water (a) $\frac{t_s}{H_l} = 0.05$ and (b) $\frac{t_s}{H_l} = 0.1$ [10].

The fundamental natural frequency (ω_f) of wall vibration is expressed as:

$$\omega_f = (\Omega_f^2 D / [\rho_s t_s H_s^4])^{1/2} \tag{12}$$

where ρ_s, Ω_f and D are the mass density, the dimensionless natural frequency of wall vibration displayed in Fig. 3 and the flexural rigidity of the tank wall respectively.

$$D = \mathrm{E} t_s^3 / (12[1 - \nu^2]) \tag{13}$$

in which E and ν are the Young's modulus and the Poisson's ratio of the tank wall respectively.

3. Model of isolation systems

A simplified model can be used for all isolation bearings used in practice [10]. In this study, the behavior of isolation systems is represented by a simplified model as shown in Fig. 4. It shows an idealized force-displacement relation of an isolation system. Three main parameters are needed to define the horizontal behavior of the bearings; namely the elastic stiffness (k_e), the post-elastic stiffness (k_p) and the characteristic strength (Q_d). Generally, simplified bilinear models can reflect the nonlinear characteristics of isolation systems.

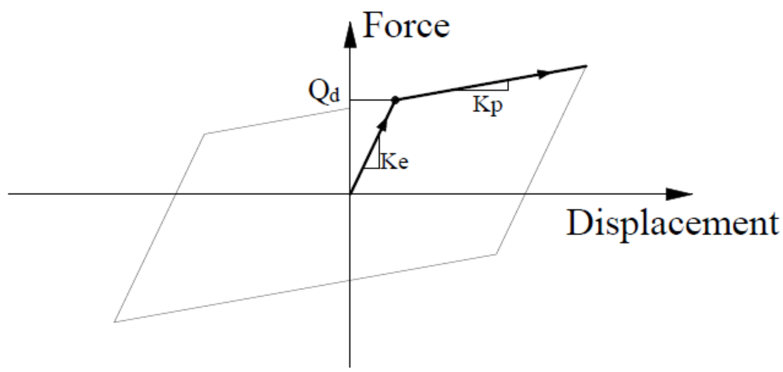


Fig. 4- Simplified bilinear model of bearing behavior

In order to isolate rectangular tanks, high damping rubber-bearing (HDRB), lead-rubber bearing (LRB) and friction pendulum bearing (FPB) are used in the present study.

4. Numerical study

The seismic response of base-isolated and non-isolated flexible rectangular fluid containers is investigated under two horizontal components of earthquake ground motion. The bi-directional interaction between the restoring forces of the isolation systems is duly considered.

Since rectangular containers are used most often for the wet-type storage of nuclear spent fuel assemblies, a typical dimension for those tanks is selected for the following example. Height of the wall, H_s =15m; wall thickness, t_s =1.2m; water depth, H_l =12m; length of the short side wall, 2Lx=20m; and length of the long side wall, 2Ly=60m. The typical material properties for the concrete tanks; are the density, ρ_s =2400kg/m^3; Young's modulus, E=2.1×10^{10} N/m^2; and the Poisson's ratio, ν =0.17.

The ground acceleration N00E and N90E of the 1995 Kobe earthquake records are applied in x- and y-direction, respectively. Properties of the mentioned earthquake is shown in Table 1. The circular natural frequency of convective mass and flexible mass for values of considered geometric aspects are determined ω_{cx} =1.19, ω_{cy} =0.53, ω_{fx} =13 and ω_{fy} =42.2rad/sec for x- and y-direction, respectively. The damping ratio of the convective mass, ξ_c , and the flexible mass, ξ_f , are taken as 0.5 and 5% in both directions, respectively. Both main horizontal components of the 1955 Kobe (JMA) earthquake records which their principle ground acceleration are 0.834g and 0.630g are applied in x- and y-direction, respectively. The values of basic, flexible and convective masses, stiffness and damping constants have been extracted from section 2 and are shown in Table 1. The main properties of the considered isolation bearings which can be used to simulate their behavior using simplified bilinear models are presented in Table 2.

Table 1- Properties of equivalent mechanical model

Variable	Mass (kg)		Stiffness (kg/mm)		Damping	
	X-direction	Y-direction	X-direction	Y-direction	X-direction	Y-direction
Basic	12.5352e6	11.4737e6	∞	∞	NA	NA
Flexible	5.9983e6	1.9863e6	1.7335e9	3.5372e9	1.0197e7	8.3821e6
Convective	5.9132e6	10.3410e6	8.6978e6	2.9554e6	7.1716e4	5.5282e4

The high damping rubber bearing (HDRB) can provide lateral flexibility so that the period of vibration is lengthened sufficiently. This system also provides damping so that the relative displacements across the flexible mounting can be limited to a practical design level. The properties related to modeling a bearing are acquired from a manufacturer and shown in Table 2.

The lead-rubber bearing (LRB) consists of alternating layers of steel and rubber which provide flexibility while maintaining sufficient vertical stiffness. The lead core in the center of the bearing provides supplemental damping. The experiments on this bearing were reported by Robinson [11]. The resulting LRB related properties cited in Table 2.

A total of forty two HDRBs and sixty five LRBs are separately used for seismic isolation of the tank models in the present study. The numbers of located HDRBs in the x- and y-direction are three and fourteen respectively, while those for LRBs are considered as five and thirteen in the x- and y-direction, respectively.

The number and properties of the bearings are chosen based on the Meggett [12] recommendations as they are reasonable values for the plastic stiffness and the yield strength of elastomeric bearings. In previous studies on the dynamic behavior of isolated multi-story buildings, Lee and Medland [13] and on the seismic isolation of bridges, Blakeley et al. [14] also suggested similar values to those concluded by Meggett for plastic stiffness and yield strength. In the present study, the elastomeric bearings are measured using the isolation period $T_b = 2.5 sec$ and the yield strength $\mathrm{Q_y} = 0.670\mathrm{W}$ and $\mathrm{Q_y} = 0.0588\mathrm{W}$ for HDRBs and LRBs, respectively. W is the part of the weight carried by the bearing.

Table 2- Main properties of isolation bearings

Isolation System	Number of Isolation Bearing	Elastic Stiffness (kN/mm)	Plastic Stiffness (kN/mm)	Yield Strength (kN)
HDRB	42	9.84	2.5	395
LRB	65	17	2	224

The friction pendulum bearing (FPB) isolation system is an axisymmetric concave sliding device that combines a high energy dissipation characteristic, and a gravitational restoring force mechanism that allows minimization of the residual displacements of the supported structure under ground shaking [15]. In this type of isolation system, the isolation period T_b is a function of the radius of the curvature (R). The isolation period T_b is given as:

$$T_b = 2\pi\sqrt{R / g} \tag{14}$$

where g is the acceleration due to gravity.

The plastic stiffness of the bearing system, which provides the restoring capability, is provided by:

$$Kp = W / R \tag{15}$$

where W is the total weight of the superstructure.

The frictional force mobilized at a sliding system is assumed to be in one horizontal direction. The limiting value of the frictional force, Qd, to which the sliding system can be subjected in a particular direction, is expressed as:

$$Q_d = \mu W \tag{16}$$

where μ is the friction coefficient of the sliding system and it can be approximated from reference [16] by the following equation.

$$\mu = \mu_{max} - (\mu_{max} - \mu_{min}) exp(-a|\dot{U}|) \tag{17}$$

where μ_{max} and μ_{min} are the maximum and minimum mobilized friction coefficients respectively. $\dot{U}$ is the velocity of sliding and a is a parameter which controls the variation of the coefficient of friction with velocity. It should be mentioned that the isolation parameters considered for the FPB are T_b=2.5sec, μ=0.06 and Δμ=0.

5. Seismic Responses

The time histories of different seismic responses for non-isolated and isolated rectangular tanks are shown in Figs. 5-7 under two horizontal components of Kobe 1995 earthquake ground motion. To investígate the effect of interaction, the responses are calculated in both unidirectional excitation (No interaction) and bidirectional excitation (Interaction). The maximum seismic response quantities for the non-isolated and isolated tanks are shown in Table 3.

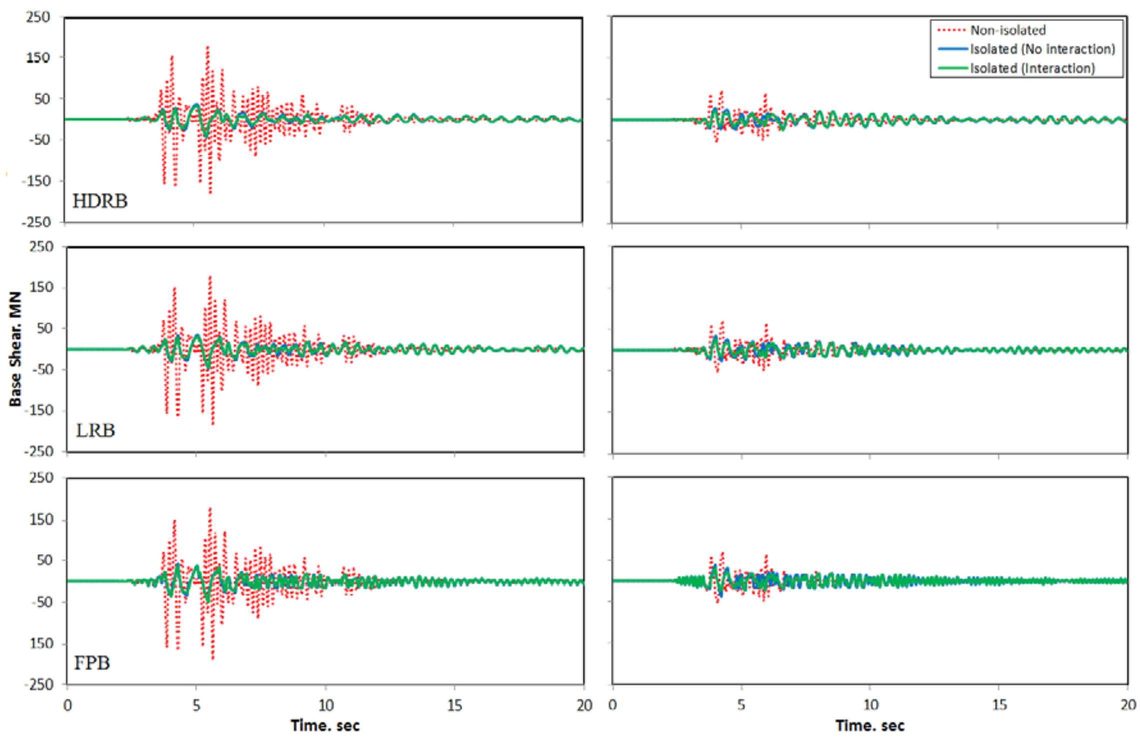
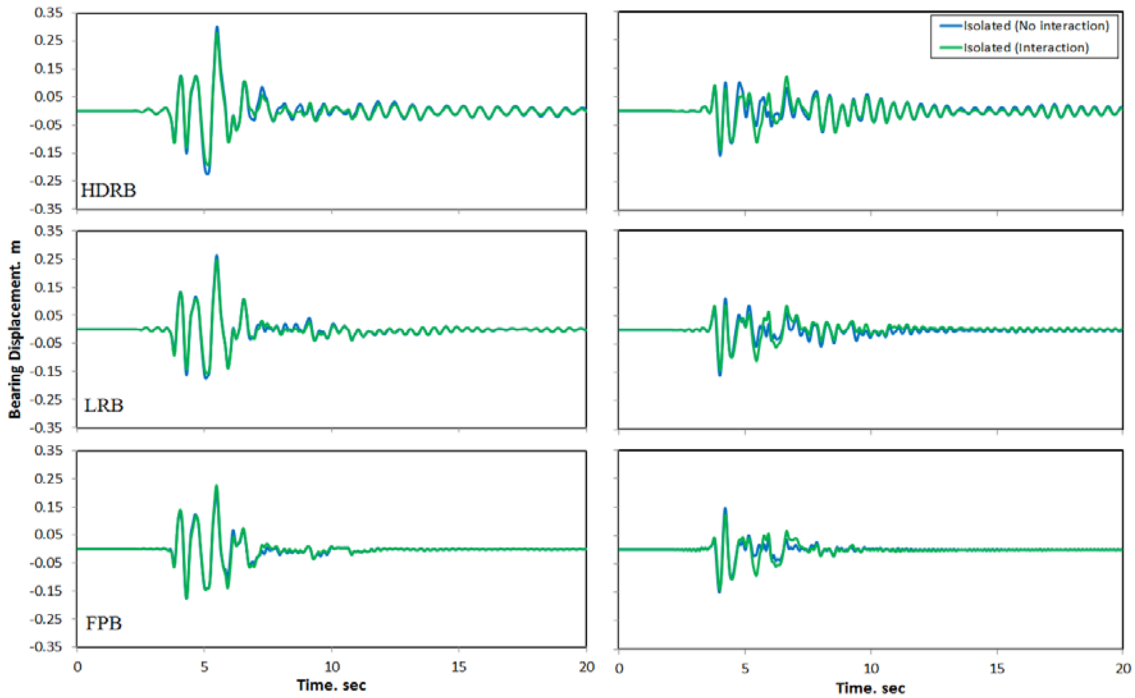
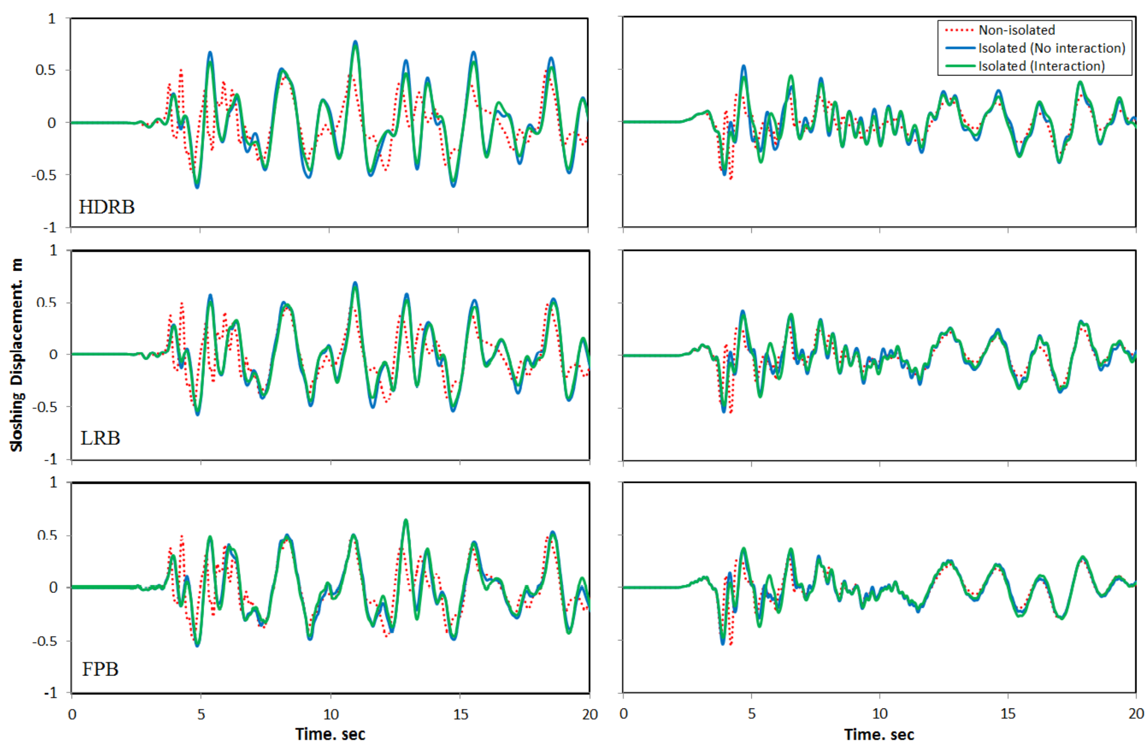


Fig. 5- Time histories of seismic base shear response in a) x-direction b) y-direction



(a) (b)

Fig. 6- Time histories of seismic bearing displacement response in a) x-direction b) y-direction



(a) (b)

Fig. 7- Time histories of liquid sloshing displacement at a) the long side wall b) the short side wall

It is observed from the figures that all three isolation systems are quite effective in reducing the base shear of liquid storage tanks. The percentage of reductions in base shear due to isolation of the tanks with interaction effect are 82.74, 82.28, and 79.40 in the x-direction for HDRB, LRB and FPB, respectively and 68.59, 62.61, and 46.09 in the y-direction for HDRB, LRB and FPB, respectively. This indicates that the reduction of base shear in isolated tanks using HDRB is more than the two other isolation bearings.

The results show that there is an increase in the sloshing displacement with the use of base isolation bearings. This is due to the high flexibility associated with the convective mass which brings its natural period closer to that of the isolated tank period. The increase in sloshing displacements when isolators were provided varied from 30% to 57% as compared to the case with no isolation system. The maximum sloshing displacement was highest in HDRB followed by LRB and FPB bearings.

An increase in displacements for all isolation systems in horizontally isolated tanks seems inevitable. The maximum values for bearing displacements of the isolated tanks are 27, 24 and 22cm in the x-direction and 12, 8 and 12cm in the y-direction for HDRB, LRB and FPB, respectively.

Comparison of the hydrodynamic pressure distributions along the height of the middle cross-section of the long and short side wall for the non-isolated and the isolated tanks are shown in Fig. 8. The hydrodynamic pressure in the middle cross-section of the wall in the case of a fixed-base tank is significantly amplified due to the fluid-structure interaction. Based on a previous study, the seismic response value in the middle of the wall for flexible rectangular liquid storage tanks was generally found to be larger than those in rigid tanks [17].

The capability of the isolation systems in reducing the hydrodynamic pressure on the wall is clearly demonstrated in this study. Smaller values are obtained when HDRB isolators are provided in both directions as compared to other isolation bearings. Overall, when base isolators are provided, the hydrodynamic pressure distribution over the height of the tank wall becomes more uniform approaching to that of parabolic distribution. The magnitude of hydrodynamic pressure is also drastically reduced for base-isolated tank. This is due to the fact that the base isolation system has a tendency to make the tank behave similar to a rigid body under horizontal ground motions.

Table 3- Comparison of maximum seismic responses

Variable		Base Shear (MN)		Bearing Displacement (m)		Sloshing Displacement (m)		Hydrodynamic Pressure (kPa)	
		x-direction	y-direction	x-direction	y-direction	Long side wall	short side wall	x-direction	y-direction
Non-isolated		180.26	70.88	NA	NA	0.49	0.29	113.95	56.91
Isolated by HDRB	No interaction	35.50	28.64	0.30	0.10	0.77	0.53	18.88	22.10
	Interaction	31.06	22.26	0.27	0.12	0.73	0.44	17.45	18.86
Isolated by LRB	No interaction	35.59	33.72	0.26	0.11	0.69	0.42	19.85	27.36
	Interaction	31.93	26.50	0.24	0.08	0.64	0.39	18.72	21.30
Isolated by FPB	No interaction	42.45	38.21	0.20	0.14	0.64	0.35	19.65	31.69
	Interaction	37.04	31.41	0.22	0.12	0.64	0.37	21.32	25.71

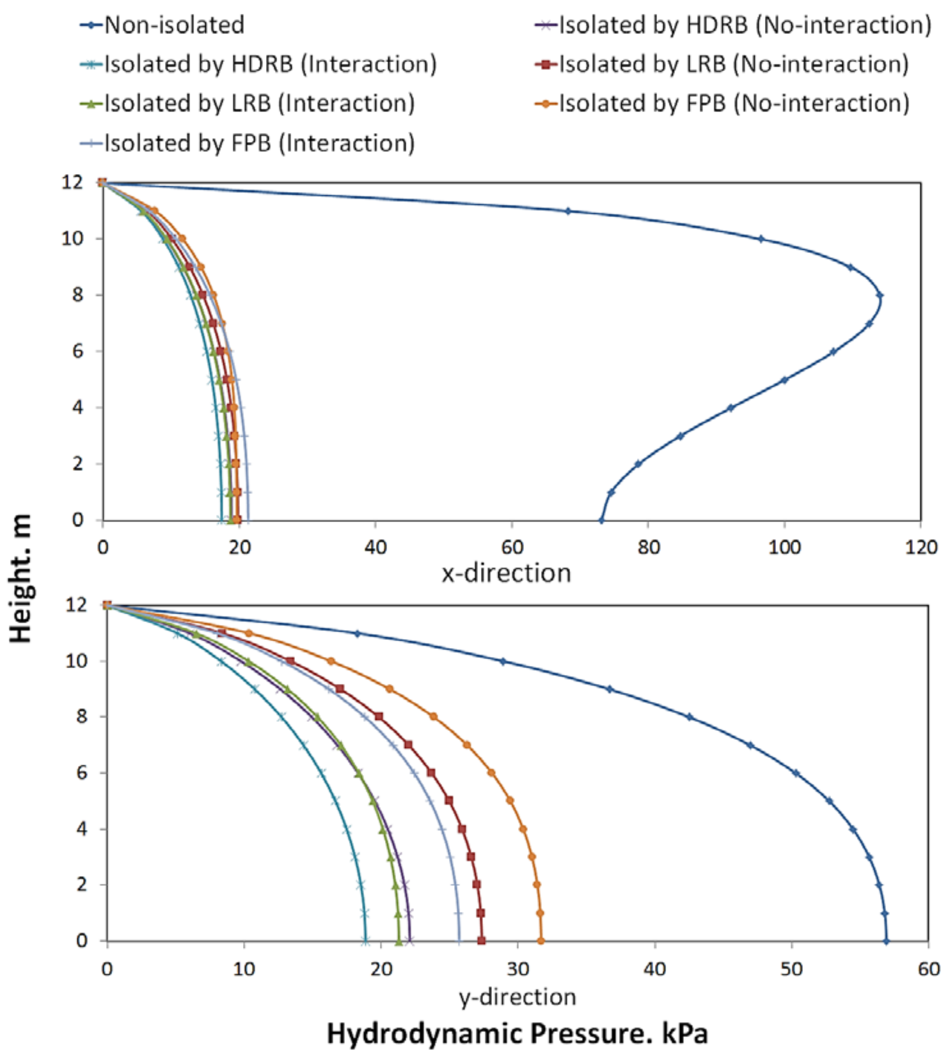


Fig 8- Comparison of hydrodynamic pressure distributions

6. Conclusions

Based on the results of this study, the following conclusions may be drawn:

1- Seismic base isolation can be considered as an effective system to reduce the seismic response values, such as base shear and hydrodynamic pressure.

2- The reduction of base shear when tanks are isolated using HDRB with interaction effect are more than those when either of the two other isolation bearings are used.

3- The capability of the three isolation systems in reducing the hydrodynamic pressure on the wall by more than six times as compared to non-isolated tanks is clearly demonstrated. Such a reduction in response for tanks isolated by HDRB, LRB and FPB shows that these isolation systems are highly effective. The isolation systems drastically changes the hydrodynamic pressure distribution over the height of the wall to a uniform distribution which can be attributed to mere behavior similar to a rigid boy.

4- An increase in displacements for all isolation systems in horizontally isolated tanks in both excitations seems to be inevitable. As a result, the tank and its accessories such as connecting pipes should be able to accommodate such movements. However, the isolation system can be designed to reduce such displacements by appropriately selecting its mechanical properties.

5- The seismic isolation systems are found to increase the sloshing displacements which is considered as significant especially for tanks isolated using HDRBs.

6- Seismic response of isolated tanks is not very sensitive to the interaction effect of the bearing forces.

A careful selection of isolators with appropriate mechanical properties is required for the optimal seismic design of rectangular containers.

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