Ain Shams Engineering Journal (2011) 2, 33–42

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CIVIL ENGINEERING

Seismic response of base isolated liquid storage ground tanks

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Received 3 December 2010; revised 5 February 2011; accepted 5 May 2011
Available online 14 June 2011

KEYWORDS
Ground liquid storage tanks;
Seismic isolation systems;
Aspect ratio;
Isolation period;
Broad;
Slender

Abstract In this paper, the seismic responses of base-isolated broad and slender cylindrical liquid storage ground tanks are investigated. Three types of isolation systems are considered. The seismic responses are compared with the corresponding responses of non-isolated tanks. Moreover, a parametric study was conducted to evaluate the effect of tank aspect ratio, isolation period, and friction coefficient of the FPS system on key responses of the tank. It was found that, base isolation is quite effective in reducing the earthquake response of ground liquid storage tanks. Generally speaking, 50–90% reductions in both base shear and impulsive displacement responses were observed. The convective displacement was observed to be 20–70% higher than that associated with fixed base tanks leading to an essential need of increasing the clear height above the liquid surface. Base isolation was found to be more effective for slender tanks in comparison with broad tanks.

1. Introduction

Liquid storage tanks have always been an important link in the distribution of water, chemical and refined petroleum products. The seismic performance of these tanks has been a matter of special importance, beyond the economic value of the structure, due to the requirement to remain functional after a major earthquake event. Water supply is essential immediately following destructive earthquakes, not only to cope with possible subsequent fires, but also to avoid outbreaks of disease. Another reason is the potential danger associated with the failure of tanks containing highly inflammable products, which can lead to extensive uncontrolled fire, while possible spillage of such contents might cause extensive environmental damage and affect populated areas.

In the past, failure of a number of ground supported liquid storage tanks occurred. Such failures generated lot of interest

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Peer review under responsibility of Ain Shams University.
doi:10.1016/j.asej.2011.05.001

Production and hosting by Elsevier

to safeguard these tanks against seismic forces. Due to the fact that conventional strengthening of tanks does not ensure absolute safety during strong earthquake ground motions, engineering researchers are developing other techniques such as base isolation for the protection of liquid storage tanks. For example, Malhotra [1] presented a new method for seismic isolation of cylindrical, ground-supported, liquid storage steel tanks by disconnecting the wall of the tank from the base plate and supporting it on a ring of horizontally flexible bearings. Wang et al. [2] studied the seismic isolation of rigid cylindrical ground tanks using friction pendulum bearings (FPS). Shrimali and Jangid [3] investigated the seismic response of liquid storage tanks isolated by lead-rubber bearings under bi-directional earthquake excitation. Shrimali and Jangid [4] studied the response of liquid storage ground tanks isolated by sliding systems. Seleemah [5] studied the performance of various degrees of frictional coefficients of sliding isolation systems due to short and long-term contamination of the sliding interfaces. Shrimali and Jangid [6] presented three analytical studies for the seismic response of base-isolated ground liquid storage tanks. Cho et al. [7] studied the seismic response of base-isolated liquid storage tanks considering fluid–structure–soil interaction in the time domain using a coupling method that combines the finite elements and boundary elements. Gregoriou et al. [8] conducted a seismic analysis of liquefied natural gas tanks isolated by rubber bearings. The problem was solved numerically by means of a detailed finite element model, taking into account fluid–structure interaction effects. Shekari et al. [9] studied seismically isolated cylindrical liquid storage tanks using a coupled boundary element-finite element to represent the fluid–structure interaction. Abalı and Uckan [10] studied both broad and slender tanks isolated by FPS bearings. They utilized Haroun and Housner's [11] model to represent the fluid. Moreover, they took the effects of overturning moments and vertical accelerations on the variation of the axial load of the bearings into consideration.

In this paper, the seismic response of cylindrical liquid storage ground tanks isolated by elastomeric or sliding bearings is investigated. The specific objectives of the study are: (i) to investigate the effectiveness of elastomeric or sliding bearings for seismic isolation of liquid storage tanks by comparing the response of the tank with and without isolation; (ii) to investigate the influence of various parameters, such as tank aspect ratio, isolation period, and the friction coefficient of an FPS system, on peak responses of the tanks. The present study includes two types of elastomeric bearings (NZ and HDRB systems) and one type of sliding bearings (FPS system).

2. Simplified fluid–structure interaction

The seismic analysis of liquid storage tanks is complicated due to fluid–structure interaction of the system. Therefore, complex actions must be taken into account. First of all, the contained liquid is interacting with the tank wall. Seismic energy is transferred from the ground to the fluid through the motion of the tank. A portion of the liquid accelerates with the tank, acting as an added mass; the remaining liquid is assumed to slosh. Sloshing occurs in the upper part of the liquid, which does not displace laterally with the tank wall, generating seismic waves. In an effort to simplify the analysis, Haroun and Housner [11] developed a three-degree-of-freedom model of a ground-supported cylindrical tank that takes tank wall flexibility into account. Following is a review of this model.

The contained liquid is considered as incompressible, inviscous and has irrotational flow. During the base excitation, the entire tank liquid mass (m) vibrates in three distinct patterns, such as sloshing or convective mass (m_c) (i.e. top liquid mass which changes the free liquid surface), impulsive mass (m_i) (i.e. intermediate liquid mass vibrating along with tank wall) and rigid mass (m_r) (i.e. the lower liquid mass which rigidly moves with the tank wall). While there are several modes in which sloshing and impulsive masses vibrates, the response can be predicted by considering only the first sloshing mode and the first impulsive mode. Therefore, the continuous liquid with flexible tank can be modeled as three lumped masses (see Fig. 1).

The convective and impulsive masses are connected to the tank by corresponding equivalent springs. The various equivalent masses and associated natural frequencies of the tank liquid are expressed as:

$$Y_c = \frac{m_c}{m} \tag{1}$$

$$Y_i = \frac{m_i}{m} \tag{2}$$

$$Y_r = \frac{m_r}{m} \tag{3}$$

$$m = \pi R^2 H \rho_w \tag{4}$$

$$\omega_i = \frac{P}{H}\sqrt{\frac{E}{\rho_s}} \tag{5}$$

$$\omega_c = \sqrt{1.84\left(\frac{g}{R}\right)\tanh(1.84S)} \tag{6}$$

where H is the liquid height, R is the tank radius, $S = H/R$ is the aspect ratio (ratio of the liquid height to radius of the tank), the non-dimensional parameters Y_c, Y_i and Y_r are mass ratios associated with convective, impulsive and rigid masses of the tank liquid, respectively; ρ_w is the mass density of liquid; ω_c and ω_i are the convective and impulsive frequencies, respectively; E and ρ_s are the modulus of elasticity and density of tank wall, respectively; g is the gravity acceleration and P is a non-dimensional parameter associated with frequency of impulsive mass. The parameters Y_c, Y_i, Y_r and P are function of the aspect ratio of the tank S, given by the following relation.

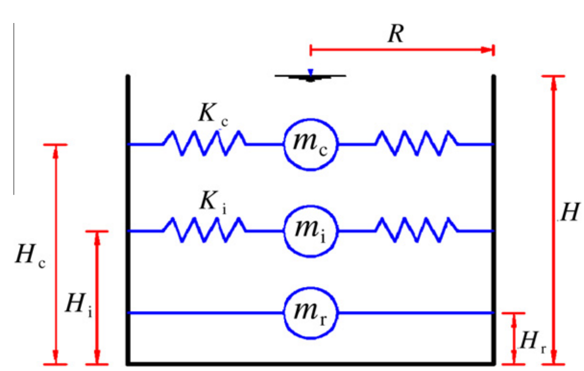

Figure 1 Mechanical analog proposed by Haroun and Housner [11] for flexible cylindrical tank.

$$\begin{Bmatrix} Y_c \\ Y_i \\ Y_r \\ P \end{Bmatrix} = \begin{bmatrix} 1.01327 & -0.8757 & 0.35708 & 0.06692 & 0.00439 \\ -0.15467 & 1.21716 & -0.62839 & 0.14434 & -0.0125 \\ -0.01599 & 0.86356 & -0.30941 & 0.04083 & 0 \\ 0.037085 & 0.084302 & -0.05088 & 0.012523 & -0.0012 \end{bmatrix} \begin{Bmatrix} 1 \\ S \\ S^2 \\ S^3 \\ S^4 \end{Bmatrix} \tag{7}$$

The centeroid of the equivalent masses m_c, m_i and m_r are at a height H_c, H_i and H_r from bottom of the tank, respectively. They are expressed in terms of non-dimensional form as:

$$\begin{Bmatrix} \mu_c \\ \mu_i \\ \mu_r \end{Bmatrix} = \begin{bmatrix} 0.52410 & -0.10792 & 0.33958 & -0.19357 & 0.04791 & -0.0045 \\ 0.44086 & -0.11972 & 0.16752 & -0.06089 & 0.00751 & 0 \\ 0.44233 & 0.08445 & 0.07916 & -0.02677 & 0.00326 & 0 \end{bmatrix} \begin{Bmatrix} 1 \\ S \\ S^2 \\ S^3 \\ S^4 \\ S^5 \end{Bmatrix} \tag{8}$$

The effective heights H_c, H_i and H_r in terms of liquid height, H, are expressed as:

$$H_c = \mu_c H \tag{9}$$

$$H_i = \mu_i H \tag{10}$$

$$H_r = \mu_r H \tag{11}$$

The equivalent stiffness and damping of the convective and impulsive masses are expressed as:

$$K_c = m_c \omega_c^2 \tag{12}$$

$$K_i = m_i \omega_i^2 \tag{13}$$

$$C_c = 2\zeta_c m_c \omega_c \tag{14}$$

$$C_i = 2\zeta_i m_i \omega_i \tag{15}$$

where ζ_c and ζ_i are the damping ratios of convective and impulsive masses, respectively.

3. Modeling of isolation systems

Program 3D-BASIS-ME designed by Tsopelas et al. [12] was utilized in this study to model the tanks including the isolation system. Following is a brief review of the models of different isolation systems used in this study.

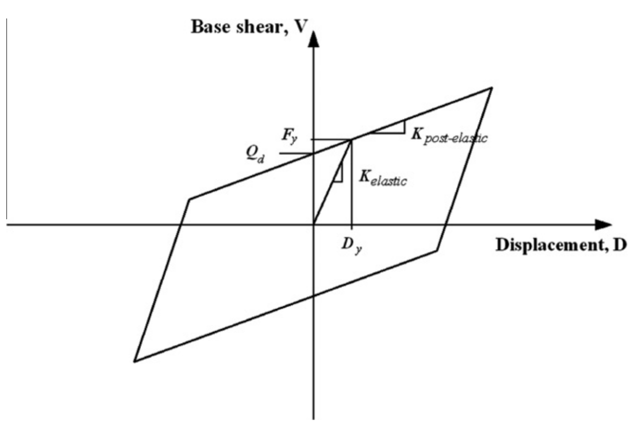

Figure 2 Idealized hysteretic force–displacement relation of NZ system.

3.1. Lead rubber bearing system (NZ system)

The behavior of lead-rubber bearings is represented by a bilinear hysteretic model. Fig. 2 shows an idealized force–displacement relation of a lead-rubber bearing. The characteristic strength, Q_d, is related to the lead plug area. The model is characterized by three parameters, namely, the post-to-pre-yielding stiffness ratio α, the yield force F_y, and the yield displacement D_y for lead-rubber bearings in which the elastic stiffness $K_{elastic}$ is approximately equal to 6.5 the post yield stiffness $K_{post\text{-}elastic}$, i.e., $\alpha = 0.154$, the yield displacement and yield force can be estimated utilizing the expressions given by FEMA [13], Yang et al. [14], and ASCE [15].

3.2. High damping rubber bearing system (HDRB system)

The behavior of HDRB system is represented by stiffening hysteretic model. Fig. 3 shows an idealized force–displacement relation of a high-damping rubber bearing. The model is characterized by six parameters, namely, the characteristic strength Q, tangent stiffness K_1, tangent stiffness K_2, Displacement limit D_1, displacement limit D_2, and yield displacement D_y.

3.3. Friction pendulum system (FPS system)

The behavior of friction pendulum bearings is represented by hysteretic model. Fig. 4 shows an idealized force–displacement

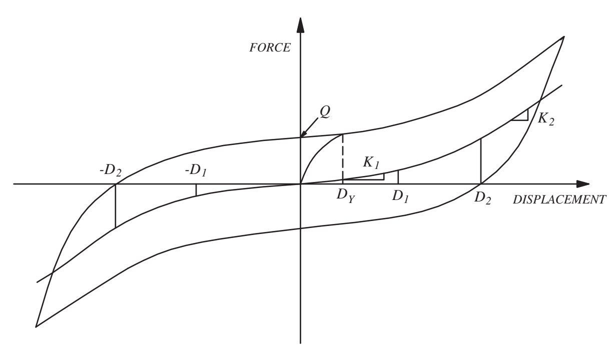

Figure 3 Stiffening hysteretic model of HDRB system.

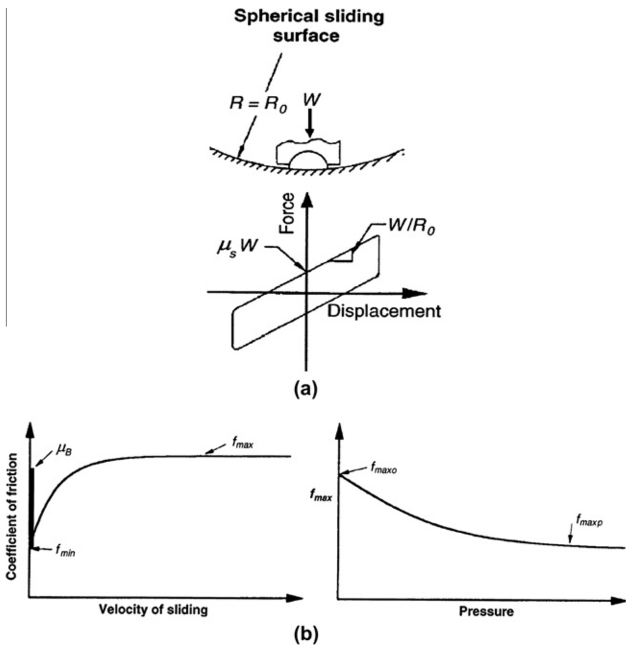

Figure 4 Modeling of a friction pendulum bearings: (a) idealized force–displacement loop and (b) relation of friction coefficient with velocity of sliding and pressure.

loop of a friction pendulum bearing. The model is characterized by six parameters, namely, the radius of curvature of the concave surface of the bearing R, maximum coefficient of sliding friction at almost zero pressure f_{max}, minimum coefficient of sliding friction f_{min}, constant which controls the transition of coefficient of sliding friction from maximum to minimum, α; yield displacement, D_y; and initial normal force at the sliding interface (static condition), N. The coefficient of sliding friction is modeled by the equation suggested by Tsopelas et al. [12] as following:

$$\mu_s = f_{max} - (f_{max} - f_{min})\exp(-a|\dot{U}|) \tag{16}$$

where $\dot{U}$ is the velocity of sliding, α is a parameter which controls the variation of the coefficient of friction with velocity. Values of parameters f_{max}, f_{min} and α have been reported in Tsopelas et al. [12], and Mokha et al. [16]. In general, parameters f_{max}, f_{min} and a are functions of bearing pressure as shown in Fig. 4b. While the overturning effect was taken into consideration, the frictional properties were assumed to be only dependent on the instantaneous sliding velocity.

Table 1 Properties of tanks.

Type of tank	H (ft)	R (ft)	$S = H/R$	t_s of wall (in.)	t_s of basemat (ft)
Broad	40	60	0.667	1	1.5
Slender	74.4	44	1.69	1.898	1.75

4. Numerical analysis of broad and slender tanks

The properties of the studied cylindrical broad and slender tanks are given in Table 1. The tank is considered as filled to a height H with water. For steel wall the modulus of elasticity is taken as $E = 29000$ Kips/in.^{2} and the unit weight, $\rho_s = 0.49$ Kips/ft^3. The liquid storage tank is represented by the mechanical system illustrated in Fig. 1 for broad or slender tanks on the basis of the theory of Haroun and Housner [11] which takes into account the deformability of the tank wall and sloshing of the fluid. For the convective mass, damping ratio is considered to be 0.005 (damping for water) and for the impulsive mass, damping is defined to be 0.02 for a steel cylindrical tank responding in the linear elastic range.

Fig. 5 represents the model of broad and slender tanks that were used in this study. The oscillators in Fig. 5 are represented as single storey, shear-type structures connected to the center of mass of the basemat. The rigid mass is rigidly attached to the concrete basemat, raising its weight. For complete investigation of the seismic behavior of liquid storage tanks, key response parameters will be compared. The main response quantities of interest are the base shear over weight of the tank (V_s/W), the convective displacement (X_c), the impulsive displacement (X_i) and the isolation system displacement (X_b).

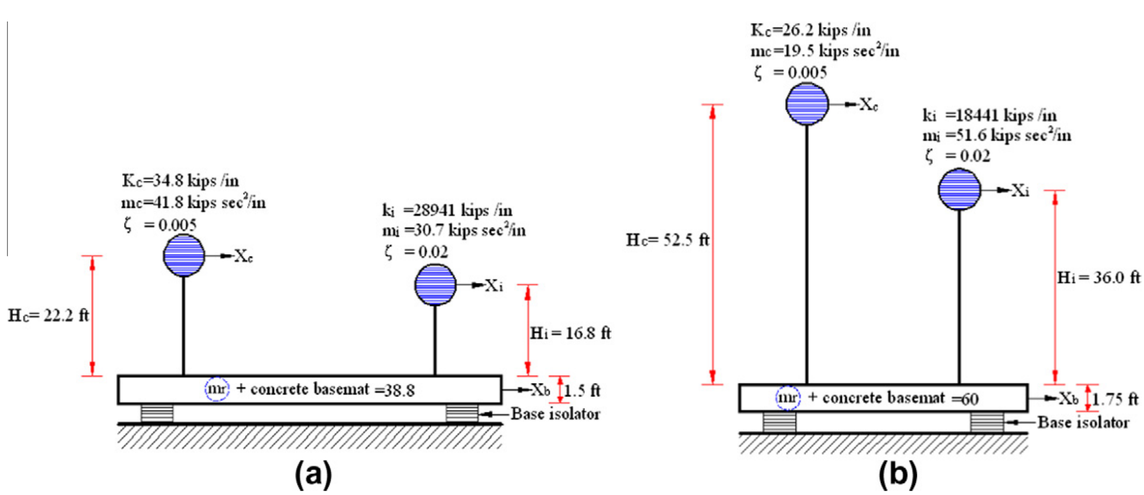

Figure 5 Idealized tank model of (a) broad tank and (b) slender tank.

5. Results and discussions

5.1. Effect of base isolation

Time variations of various response quantities of broad and slender tanks subjected to El-Centro ground excitation are illustrated in Figs. 6 and 7, respectively. The responses are shown for both isolated and non-isolated conditions. It is observed that base shear over weight (V_s/W) and impulsive displacement (X_i) of the isolated tanks for all isolation systems are significantly reduced in comparison to those without isolation system. These results are in agreement with those observed by Wang et al. [2], Shrimali and Jangid [3,4], Seleemah [5], Gregoriou et al. [8], Shekari et al. [9] and Abalı and Uckan [10]. The reduction in base shear leads to reduction in the tank wall thickness and hence more economic design. Moreover, the reduction in the impulsive displacement means reduction in the actions that cause local buckling in the tank wall. Such reductions will, of course, lead to a superior tank performance during earthquakes. It is also observed that, as a result of isolation, there is a moderate increase in the convective displacement. 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. However, such behavior has no practical consequences except for the need to increase the clear height above the liquid surface.

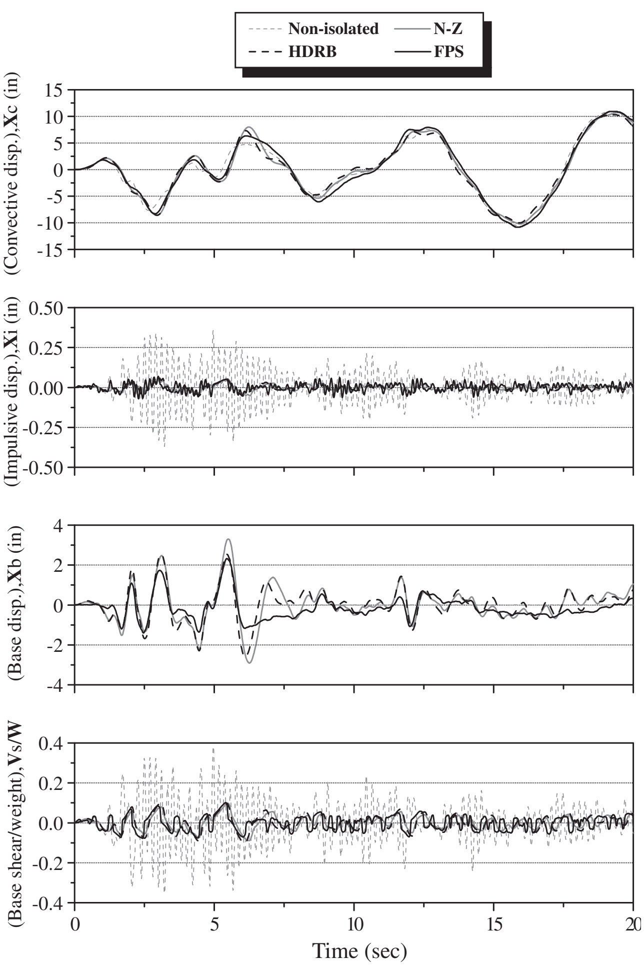

Figure 6 Time variation of response quantities of broad ground tank under El-Centro earthquake (T_b = 2 s, ζ_b = 0.1, f_{max} = 4.5% and f_{min} = 3%).

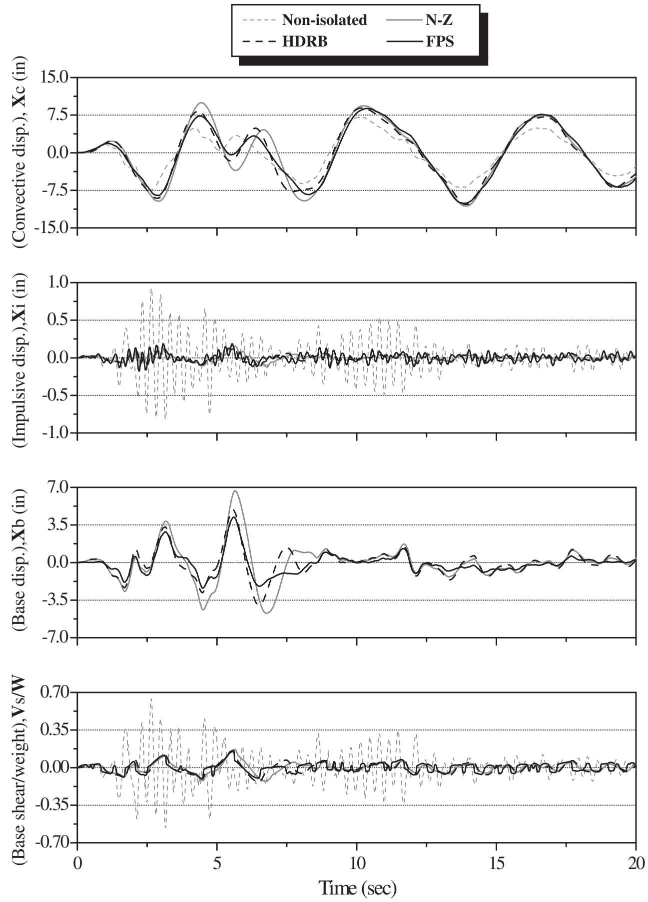

Figure 7 Time variation of response quantities of slender ground tank under El-Centro earthquake (T_b = 2 s, ζ_b = 0.1, f_{max} = 4.5% and f_{min} = 3%).

The peak response quantities for broad and slender tanks under the earthquakes considered are tabulated in Table 2. It is observed that, the average reduction percentage in the base shear are 63% and 81%; and in the impulsive displacement are 73% and 88% for broad and slender tanks, respectively. Further, the reduction of base shear and impulsive displacement for slender tank is significantly greater than that for the broad tank, implying that the seismic isolation is more effective for slender tanks. This observation is in agreement with that reported by Shekari et al. [9]. Overall results indicate that the FPS system is more effective to reduce both base shear and base displacement responses in comparison to NZ or HDRB systems.

5.2. Effect of tank aspect ratio

In order to investigate the behavior for a wide practical range of liquid storage tanks, the effect of change aspect ratio (H/R) from 0.5 to 4.0 on the peak response quantities are shown in Figs. 8 and 9. It should be mentioned that in all cases of aspect ratios the volume of the water tank was kept constant at 452389 ft^3 and the total isolated weight was kept constant at

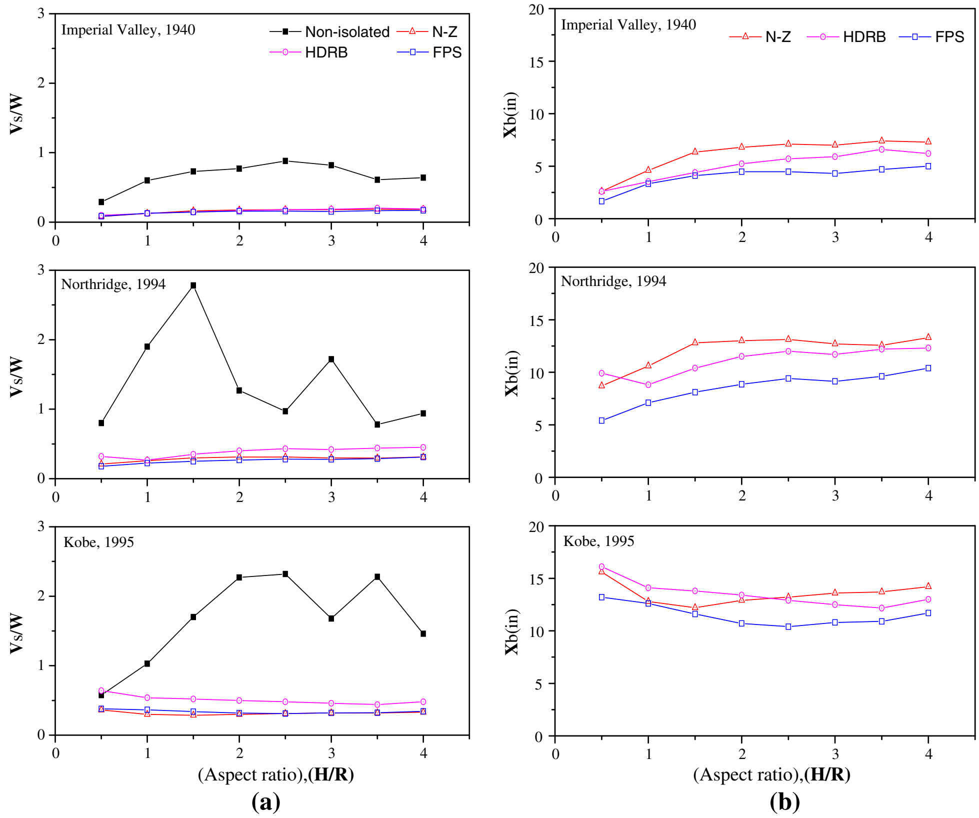

Figure 8 Effect of aspect ratio on peak response of the isolated ground tank (T_b = 2 s, ζ_b = 0.1, f_{max} = 4.5% and f_{min} = 3%): (a) base shear over weight and (b) base displacement.

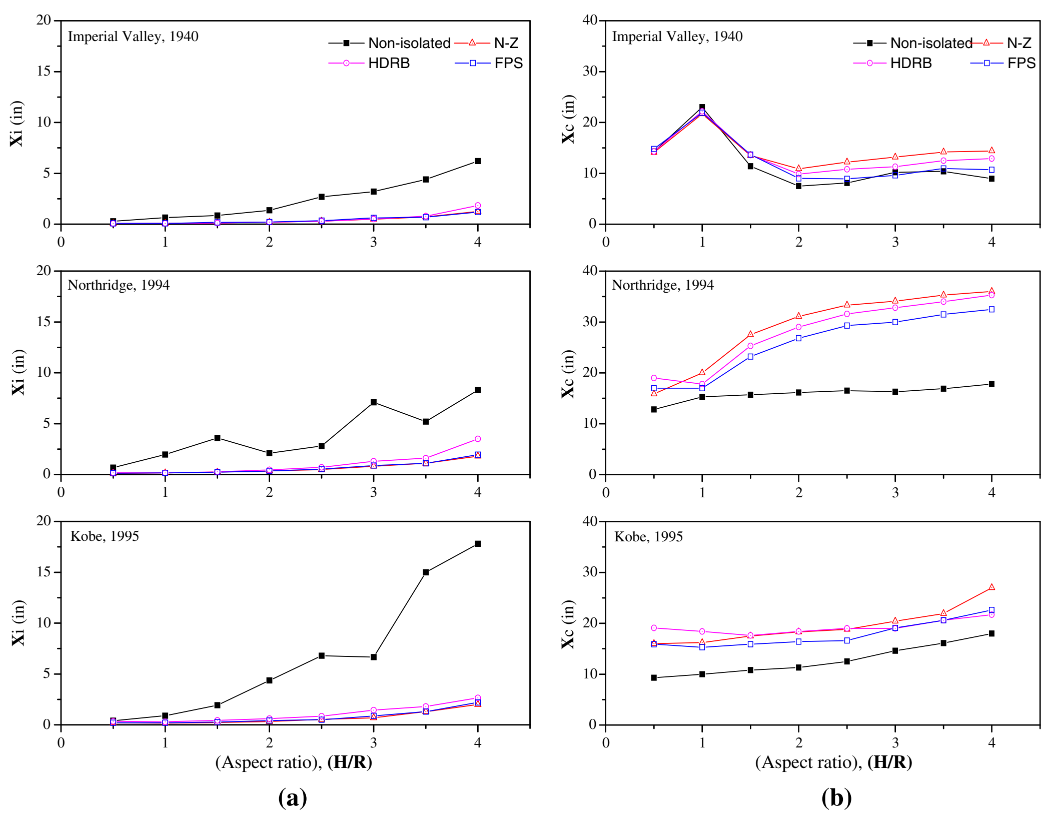

Figure 9 Effect of aspect ratio on peak response of the isolated ground tank (T_b = 2 s, ζ_b = 0.1, f_{max} = 4.5% and f_{min} = 3%): (a) impulsive displacement and (b) convective displacement.

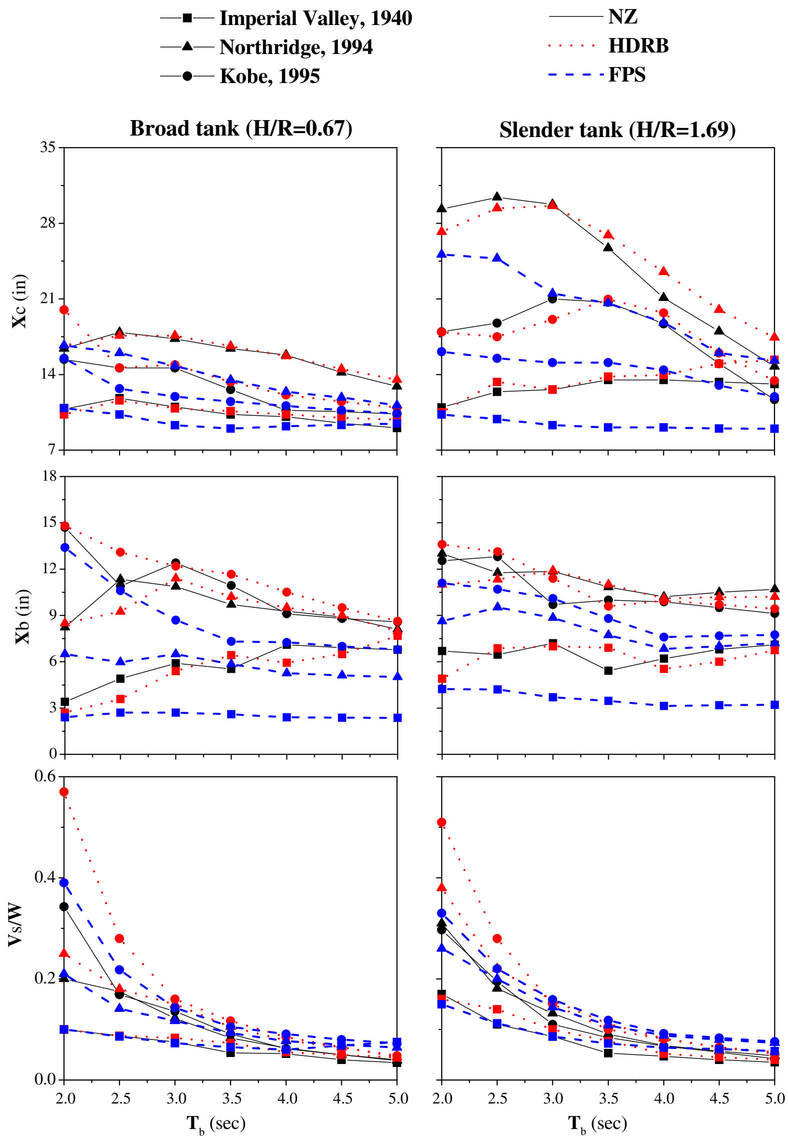

Figure 10 Effect of isolation period on peak seismic response of isolated tanks.

Table 2 Peak responses of broad and slender ground tanks.

Earthquake	Type of tank	Non-isolated tank			Isolated tank											
					N-Z system				HDRB system				FPS system			
		Xc (in.)	Xi (in.)	Vs/W	Xc (in.)	Xi (in.)	Xb (in.)	Vs/W	Xc (in.)	Xi (in.)	Xb (in.)	Vs/W	Xc (in.)	Xi (in.)	Xb (in.)	Vs/W
Imperial Valley 1940	Broad	10.91	0.38	0.39	10.70	0.05	3.30	0.10	10.26	0.06	2.62	0.10	10.90	0.07	2.32	0.10
	Slender	8.50	0.93	0.64	10.95	0.15	6.67	0.17	10.53	0.14	4.88	0.16	10.26	0.19	4.23	0.15
Northridge N90S 1994	Broad	14.30	0.64	0.75	16.30	0.12	8.15	0.20	16.91	0.14	8.62	0.26	16.86	0.14	6.46	0.21
	Slender	16.30	3.80	2.41	29.30	0.26	13.00	0.31	27.15	0.34	10.98	0.38	25.10	0.25	8.63	0.26
Kobe N00S 1995	Broad	8.93	0.51	0.78	15.50	0.18	14.80	0.34	20.20	0.30	14.74	0.57	15.70	0.22	13.50	0.39
	Slender	11.10	3.54	2.19	17.95	0.28	12.55	0.30	17.93	0.51	13.60	0.51	16.11	0.30	11.10	0.33

31550 Kips. It is observed that the base shear of the non-isolated tank is very sensitive to the change of the aspect ratio and to the change of the driving motion also. On the other hand, using any of the three isolation systems considerably reduced the base shear. Moreover, the base shear of isolated tanks is not significantly influenced by the aspect ratio and it

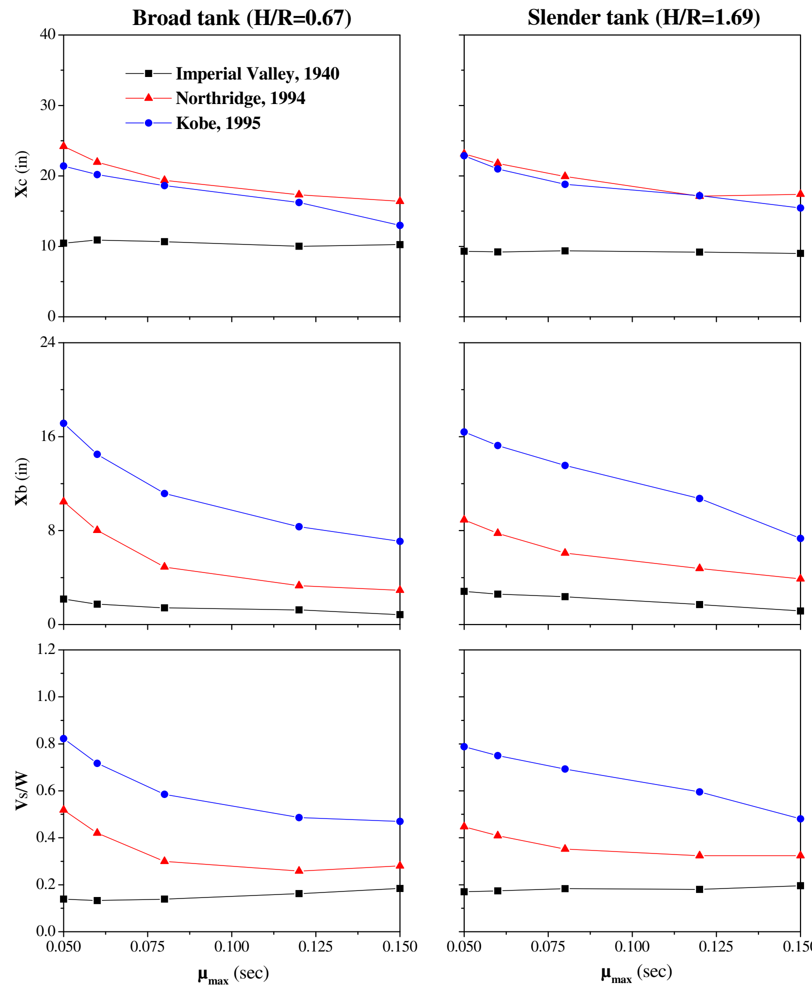

Figure 11 Effect of friction coefficient on peak seismic response of the isolated ground tank with FPS system (T_b = 2 s).

can be seen that the NZ and FPS systems are slightly better than the HDRB system. The base displacement is nearly flat for aspect ratios in the range 2–4, with the lowest response associated with FPS system.

Fig. 9 shows that the impulsive displacement of the non-isolated tank considerably increases with the aspect ratio leading to high probability of local buckling occurrence in the steel walls of the tanks. On the other hand, the impulsive displacements of the isolated tank are not only much less than those of the non-isolated tank but also show a very slight increase with the aspect ratio (low probability of local buckling occurrence in steel wall of the tank). Again NZ and FPS systems are slightly better than the HDRB system.

Fig. 9 also shows that in general the convective displacement increases with the aspect ratio of the tank. In the case of isolated tank the convective displacement increases by an order of 20–70% due to overall flexibility of the system caused by seismic isolation. Such increase requires that the clear height of the tank should be increased to prevent spillage of the contained liquid or extra forces acting on the tank roof. The FPS system has the least convective displacement as compared to NZ or HDRB systems.

From the results shown in Figs. 8 and 9 it can be stated that seismic isolation is quite effective in the reduction of most important response values (base shear and impulsive displacement) for all aspect ratios. Moreover, the use of FPS system gives superior performance as compared to NZ or HDRB systems. Nevertheless, the clear height over the liquid surface should be increased especially in slender tanks.

5.3. Effect of isolation period

Fig. 10 show the variation of peak response of broad (H/R = 0.67) and slender (H/R = 1.69) tanks against the isolation period. It is observed that, as the flexibility of isolation system increases the peak base shear reduces. This is due to the fact that increased flexibility of the isolation systems transmits less acceleration to the structure. Moreover, for a relatively short isolation period (say less than 3.0 s) the base shear is significantly dependent on the earthquake excitation. However, as the isolation period approaches 5.0 s, nearly all systems result in a very narrow band of base shear level even for different earthquakes and different aspect ratios. The base displacement seems to be nearly flat for T > 3.5 s. The convective displacements of the tank are earthquake dependent and generally decrease with the increase of the period of the isolation system. Thus, using isolation period of 4.0–5.0 s might be recommended.

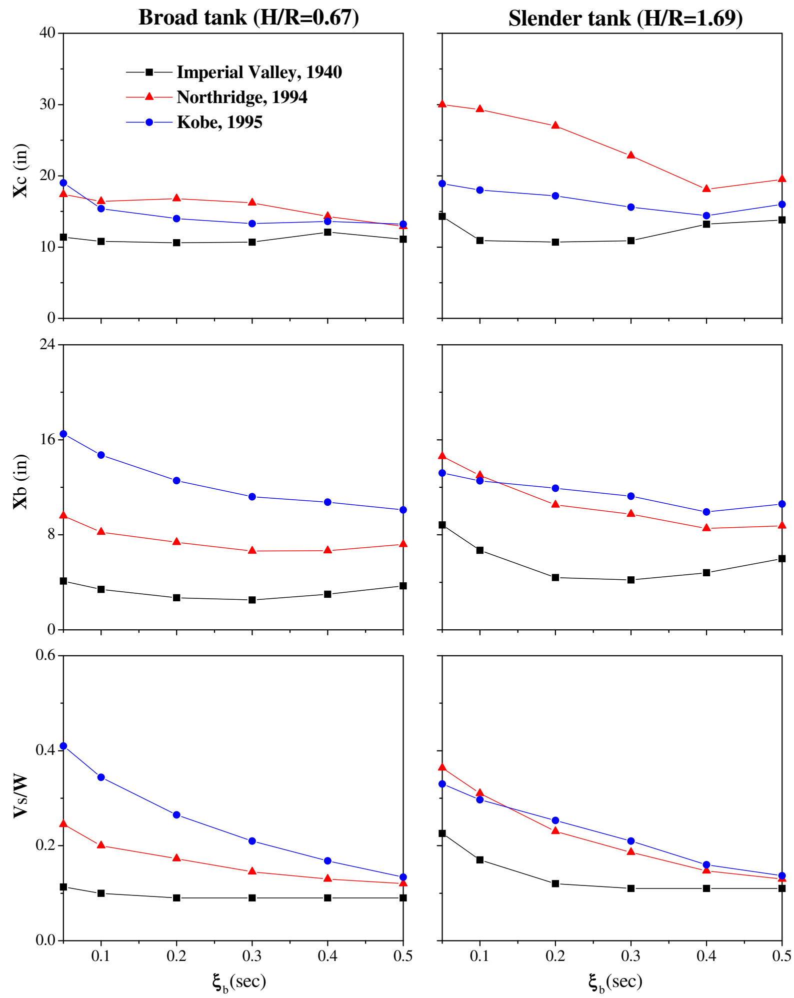

Figure 12 Effect of bearing damping on peak seismic response of isolated ground tank with NZ system ($T_b = 2$ s).

5.4. Effect of friction coefficient of FPS system and damping of NZ system

The effect of coefficient of friction, μ_{max}, and bearing damping of NZ system on the resulting response of isolated broad and slender tanks are shown in Figs. 11 and 12, respectively. Generally speaking, increase of the friction coefficient or bearing damping dissipates more seismic energy and hence causes most response parameters to decrease.

6. Conclusions

From the results of the present study, the following conclusions can be stated:

- Base isolation is quite effective in reducing the earthquake response of ground liquid storage tanks, base shear reductions ranged between 50% and 90% and impulsive displacement reductions ranged between 65% and 90%.
- The base isolation is more effective for slender tanks in comparison with broad tanks.
- There is a moderate increase (20–70%) in the convective displacement when the tank is seismically isolated especially for high aspect ratios. Nevertheless, the clear height over the liquid surface should be increased to overcome such disadvantage.
- Performance of FPS system proved to be better as compared to the other isolation systems.
- For the non-isolated tanks, the base shear and the impulsive displacement are significantly affected by the aspect ratio and the exciting earthquake also. On the other hand, for the isolated tanks, these response parameters are significantly reduced and show negligible dependency on the aspect ratio. This holds true for all types of utilized isolation systems.
- The impulsive displacements of the non-isolated tanks considerably increase with the aspect ratio leading to high probability of local buckling occurrence in the steel walls of the tanks. On the other hand, for the isolated tanks they are not only significantly reduced but also show a negligible increase with the aspect ratio leading to low probability of local buckling occurrence in steel walls of the tanks.
- Increase in the friction coefficient of FPS system or bearing damping of NZ system dissipate more seismic energy and hence causes most response parameters to decrease.
- Isolation period of 4.0–5.0 s can be recommended.

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