Seismic Response of Elevated Liquid Storage STEEL Tanks Under Bi-direction Excitation

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Abstract

Seismic response of elevated cylindrical liquid storage steel tanks isolated by resilient-friction base isolator is investigated under two horizontal components of real earthquake ground motion. The continuous tank liquid mass is lumped as sloshing mass, impulsive mass and rigid mass. The corresponding equivalent stiffness associated with these lumped masses is computed from properties of the contained liquid and tank wall. The governing equations of motion of the isolated tank are derived and solved iteratively. The frictional forces mobilized at the interface of the sliding system are assumed to be velocity dependent and their interaction in two horizontal directions is duly considered. A parametric study is also conducted to study the effects of important system parameters on the effectiveness of seismic isolation of the liquid storage tanks. The various parameters considered are (i) aspect ratio of tank, (ii) the period of isolation, (iii) the damping of isolation bearings and (iv) the coefficient of friction of the resilient-friction-base-isolator. It has been found that the bi-directional interaction of frictional forces have noticeable effects and if these effects are ignored then the sliding base displacements will be underestimated which can be crucial from design point of view.

Keywords: seismic response, elevated liquid storage tank, resilient friction base isolator system, bi-directional interaction, system parameters

1. Introduction

The protection of civil engineering structures is a world wide priority of most current importance. Such protection may range from reliable operation, comfort and survivability of buildings, towers, pipelines, bridges and liquid storage tanks. In like events which cause the need for such protective measures are earthquake, wind, waves, traffic etc. Indications are that control methods will be able to make a genuine contribution to this problem area, which is of great economic and social importance. There are various control methods such as passive control, active control and semi-active control methods. The passive control method is one which needs no external power and gets activated as soon as the ground motions strike the structures; however, the activation of other systems depends upon the external power supply. Secondly, the sliding system, which is a passive control system, effective for a wide range of frequency band.

The integrity of a structure can be protected from the attack of severe earthquakes either through the concept of resistance or isolation. In designing a structure by resistance, it is assumed that the earthquake forces are directly transmitted to the structure and each member of the structure is required to resist the maximum possible forces that may be induced by earthquakes based on various ductility criteria. In the category of earthquake isolation, however, one is interested in reducing the peak response of the structure through implementation of certain isolation devices between the base and foundation of the structure which prevents the transmission of earthquake acceleration. The main concept in isolation is to increase the fundamental time period of structural vibration beyond the energy containing periods of earthquake ground motion. The other purpose of an isolation system is to provide an additional means of energy dissipation, thereby reducing the transmitted acceleration into the superstructure. This innovative design approach aims mainly at the isolation of a structure from the supporting ground, generally in the horizontal direction, in order to reduce the transmission of the earthquake motion to the structure.

A variety of isolation devices including elastomeric bearings (with and without lead core), frictional-sliding bearings and roller bearings have been developed and used practically for aseismic design of buildings during the last two decades (Buckle and Myres, 1990). A significant amount of recent research in the base isolation has focused on the use of frictional elements to concentrate flexibility of the structural system and to add damping to the isolated structure. The most attractive feature of the frictional base isolation system is its...
effectiveness for a wide range of frequency input. The other advantage of a frictional type system is that it ensures the maximum acceleration transmissibility equal to the maximum limiting frictional force. The simplest sliding system device is pure-friction (P-F) system without any restoring force (Jangid, 1997). More advanced devices involve pure-friction elements in combination with a restoring force. The restoring force in the sliding system reduces the base displacements and brings back the system to its original position af-er an earthquake. Some of the commonly proposed sliding systems with restoring force include the resilient-friction base isolator, R-FBI system (Mostaghel and Khodaverdian, 1990), the friction pendulum system, FPS, (Zayas et al., 1990), Electricite de France system, EDF, (Gueraud et al., 1985) and elliptical rolling rods (Jangid and Londhe, 1998). The sliding systems performs very well under a variety of severe earthquake loading and are very effective in reducing the large levels of the superstructure's acceleration without inducing large bearing displacements (Mostaghel and Khodaverdian, 1990; Fan and Ahmad, 1990). In addition, the sliding systems are also less sensitive to the effects of torsional coupling in asymmetric base-isolated buildings (Jangid and Dutta, 1995). The two numerical solution techniques used for isolated structures, namely conventional and hysteretic give same results for same parameters of the structure except P-F system (Jangid, 2005).

There had been several studies for investigating the effectiveness of seismic isolation for buildings but a very few studies are reported for seismic isolation of liquid storage tanks which has a vital and strategic use. Kim and Lee (1995) experimentally investigated seismic performance of ground supported liquid storage tank isolated by elastomeric bearings and found that the isolation system is effective to control the dynamic response. Malhotra (1997a,b) and Chalhoub and Kelly (1988) found that isolation is effective to control the response of the tanks except marginal increase of sloshing height. It is observed that the seismic response of isolated liquid storage tanks is reduced significantly in comparison to corresponding non-isolated liquid tank (Shrimali and Jangid, 2002; Jadhav and Jangid 2006). But there are limited studies for performance of the elevated liquid storage tanks. Bleiman and Kim (1993), Shenton III and Hampton (1999) and Shrimali and Jangid (2003), carried out the response of elevated isolated liquid tanks. It is to be noted that in all the above studies the elastomeric bearings had been used and there is a need to study the performance of sliding systems for seismic isolation of elevated liquid storage tanks. In the isolated liquid tank the liquid vibrates in three distinct patterns, namely sloshing mass, impulsive mass and rigid mass. Park et al. (2000) carried out the experimental studies on pool type tank isolated with linear isolation system and compared with numerical results and found that higher sloshing mode may be influenced at higher exciting frequency. However, for friction base isolation system the fundamental mode is the predominant (Wang et al., 2001; Malhotra 1997a,b).

In this paper, response of elevated liquid storage tanks isolated by the resilient-friction base isolation (R-FBI) system under two horizontal components of an earthquake ground motion is investigated. The specific objectives of the present study can be summarized as (i) to present a method for earthquake analysis of liquid storage tanks supported on sliding systems by duly incorporating the effects of bi-directional interaction (by comparing the response of the system with and without interaction), and (ii) to study the influence of important parameters on the effectiveness of the sliding system for liquid storage tanks. The various important parameters considered are: the period, damping, friction coefficient of sliding system and the aspect ratio of the tank.

2. Model of Liquid Storage Steel Tank and the Sliding System

Fig. 1 shows an idealized 2-D model of cylindrical elevated liquid storage steel tank supported on the resilient-friction base isolation system. For this study, the two tank models considered are: tank with isolation at base (referred as isolated model-I) and another model in which the isolation system is provided at top of the tower structure (referred as isolated model-II). The contained liquid is considered as incompressible, inviscid and has irrotational flow. During the base excitation, the entire tank liquid mass vibrates in three distinct patterns such as sloshing mass (i.e. top liquid mass which changes the free liquid surface), impulsive mass (i.e. intermediate liquid mass vibrating along with tank wall) and rigid mass (i.e. the lower liquid mass which rigidly moves with the tank wall). It has been observed that fundamental mode of the three masses are dominating the response (Housner 1963; Rosenblueth and Newmark 1971, Malhotra 1997b). The lumped masses are: sloshing, impulsive and rigid masses referred as $m_s$, $m_i$ and $m_r$ respectively. The sloshing and impulsive masses are connected to the tank wall by corresponding equivalent spring having stiffness $k_s$ and $k_i$ respectively. The damping constant of the sloshing and impulsive masses are $c_s$ and $c_i$, respectively. The system has eight-degrees-of-freedom under bi-directional earthquake ground motion, two-degrees-of-freedom at each lumped mass in two horizontal x and y-directions. These degrees of freedom are denoted by $(u_{x0}, u_{y0})$, $(u_{x0}, u_{y0})$, $(u_{x0}, u_{y0})$ and $(u_{x0}, u_{y0})$ which denote the absolute displacement of sloshing mass, impulsive mass, tower structure and base mass in x and y-directions, respectively. Further, the self-weight of steel tower structure and base mass (i.e. mass of base plate) are assumed to be 10 percent and 5 percent of the tank liquid, respectively. The parameters of the tanks considered are liquid height $H$, radius, $R$ and average thickness of tank wall, $t$. The effective masses are defined in terms of the liquid mass, $m$ from the parameters expressed (Haroun, 1983) as
where $S = H/R$ is the aspect ratio (i.e. ratio the liquid height to radius of the tank) and the non-dimensional parameters $Y_c$, $Y_i$, and $Y_r$ are the mass ratios defined as

$$Y_c = \frac{m_c}{m}$$  \hspace{1cm} (2)$$

$$Y_i = \frac{m_i}{m}$$  \hspace{1cm} (3)$$

$$Y_r = \frac{m_r}{m}$$  \hspace{1cm} (4)$$

$$m = \pi R^2 H \rho_w$$  \hspace{1cm} (5)$$

The natural frequencies of sloshing mass, $\omega_c$, and impulsive mass, $\omega_i$, are given by the following expressions

$$\omega_c = \sqrt{\frac{g}{R} \tanh \left(1.84 \frac{H}{R} \right)}$$  \hspace{1cm} (6)$$

$$\omega_i = \frac{P}{E} \left( \frac{H}{H_1} \rho_s \right)$$  \hspace{1cm} (7)$$

where $E$ and $\rho_s$ are the modulus of elasticity and density of tank wall, respectively; $g$ is the acceleration due to gravity.

The sliding system considered is isotropic (i.e. same coefficient of friction in two orthogonal directions of the motion in the horizontal plane) and the restoring force provided by the sliding system is considered to be linear (i.e. proportional to relative displacement). The additional damping (other than friction) is assumed as viscous damping. The frictional forces mobilized at sliding system are assumed to be coupled in two horizontal directions (interaction) and the friction coefficient is assumed to be independent on the relative velocity (Fan and Ahmadi,
1990; Constantinou et al., 1990). The limiting value of the frictional force, \( Q \), to which the sliding system can be subjected in a particular direction is expressed as

\[
Q_i = \mu M g
\]

where \( \mu \) is the friction coefficient of the sliding system; and \( M \) (i.e. \( m_t + m_b + m_p \)) is the effective mass of the tank (the mass of tank wall is neglected since it is very small in comparison to the effective liquid mass).

3. Governing Equations of Motion

The equations of motion of isolated liquid storage tank (Isolated-I) subjected to earthquake ground motion are expressed in the matrix form as

\[
[\{m\}] \ddot{[\{z\}]} + [\{c\}] \dot{[\{z\}]} + [\{k\}] [\{z\}] = -[\{m\}] [\{r\}]
\]

where \( \{z\} = \{x_c, x_i, x_s, x_b, y_c, y_i, y_s, y_b\}^T \) and \( \{Q\} = \{0, 0, 0, Q_{x}, 0, 0, 0, Q_{y}\}^T \) are the relative displacement and frictional force vector, respectively; \( x_c = u_{cx} - u_{bx} \) and \( y_c = u_{cy} - u_{by} \) are the displacements of the sloshing mass relative to bearing displacements in \( x \) and \( y \)-directions, respectively; \( x_i = u_{ix} - u_{bx} \) and \( y_i = u_{iy} - u_{by} \) are the displacements of the impulsive mass relative to bearing displacements in \( x \) and \( y \)-directions, respectively; \( x_s = u_{sx} - u_{bx} \) and \( y_s = u_{sy} - u_{by} \) are the displacement of tower relative to bearing displacement in \( x \) and \( y \)-directions, respectively; \( x_b = u_{bx} - u_{bx} \) and \( y_b = u_{by} - u_{by} \) are the displacements of the bearings relative to ground in \( x \) and \( y \)-directions, respectively; \( [m], [c] \) and \( [k] \) are the mass, damping and stiffness matrices, respectively; \( [r] \) is the frictional force vector; \( u_{g} = \{u_{gx}, u_{gy}\} \) is the earthquake ground acceleration vector; \( (Q_{x}, Q_{y}) \) are the ground accelerations and the frictional forces in the \( x \) and \( y \)-directions of the system, respectively; and \( T \) denotes the transpose. For Isolated-II interchange tower and bearing degree-of-freedom take place. Further, for non-isolated tank \( \{Q\} \) will be a null vector.

4. Criteria for Sliding and Non-Sliding Phases

In a non-sliding phase \( (\dot{x}_b - \dot{y}_b = 0 \) and \( \dot{x}_b - \dot{y}_b = 0 \) \) the resultant of the frictional forces mobilized at the sliding system interface is less than the limiting frictional force (i.e. \( \sqrt{Q_{x}^2 + Q_{y}^2} < Q \)). The system starts sliding \( (\dot{x}_b \neq 0 \) and \( \dot{y}_b \neq 0 \) \) as soon as the resultant of the frictional forces attains the limiting frictional force. Thus, the sliding of the system takes place if

\[
Q_{x}^2 + Q_{y}^2 = Q_i^2
\]

Note that the Eq. (10) indicates a circular interaction between the frictional forces mobilized at the interface of the sliding system as shown in Fig. 2(a). The system remains in the non-sliding phase inside the interaction curve. Further, the governing equations of motion in two orthogonal directions of the structures supported on the sliding type of isolator are coupled during the sliding phases due to interaction between the frictional forces. However, this interaction effect is ignored if the structural system is modelled as a 2-D system. In such cases the corresponding curve which separates the sliding and non-sliding phases is a square as shown in Fig. 2(a) by dashed lines.

Since the frictional forces oppose the motion of the system, the direction of the sliding of the system with respect to the \( x \)-direction is expressed as

\[
0 = -\tan^{-1} \left( \frac{\dot{y}_b}{\dot{x}_b} \right)
\]

5. Solution of Equations of Motion

During the non-sliding phase \( (\dot{x}_b - \dot{y}_b = 0 \) and \( \dot{x}_b - \dot{y}_b = 0 \) \), the rigid mass sticks to the foundation and the system
behaves as three single-degree-of-freedom (i.e., sloshing, impulsive and tower drift) in two orthogonal horizontal directions. These equations can be solved by exact or numerical integration technique until the frictional forces mobilized at the sliding surface are less than the limiting value. As soon as, the frictional force attains the limiting value the sliding phase of motion begins in which the additional degrees-of-freedom of the rigid mass shall be included in the response analysis. Since the frictional forces are opposite to the motion of the system in two orthogonal directions, as a result, the equations of motion are to be solved in the incremental form during the sliding phase of motion by conventional equations of motion are expressed as:

\[ \{\Delta \{x_\Delta, x_{\Delta b}, y_\Delta, y_{\Delta b}\}\} = \{\Delta Q\} \]

(12)

where \{\Delta \{x_\Delta, x_{\Delta b}, y_\Delta, y_{\Delta b}\}\} is the incremental displacement vector; \{\Delta Q\} is the effective excitation vector; and \{\Delta \{x_\Delta, x_{\Delta b}, y_\Delta, y_{\Delta b}\}\} is the incremental frictional force vector; and \Delta Q_x and \Delta Q_y are the incremental frictional forces in the x and y-directions, respectively.

In order to determine the incremental frictional forces, consider the Fig. 2(b). Let at time \(t\) the frictional forces are at point A on the interaction curve and moves to point B at time \(t + \Delta t\). Therefore, the incremental frictional forces are expressed as:

\[ \Delta Q_x = \Delta Q_x^{+\Delta t} \cos(\theta^{+\Delta t}) - \Delta Q_x \\
\Delta Q_y = \Delta Q_y^{+\Delta t} \sin(\theta^{+\Delta t}) - \Delta Q_y \]

(13)
(14)

where \(\Delta Q_x^{+\Delta t}\) is the limiting frictional force at time \(t + \Delta t\). Since the frictional forces are opposite to the motion of the system, therefore, the angle \(\theta^{+\Delta t}\) is expressed in terms of the relative velocities of the system at time \(t + \Delta t\) by

\[ \theta^{+\Delta t} = \tan^{-1}\left(\frac{\Delta v_{bx}}{\Delta v_{by}}\right) \]

(15)

Substituting for \(\Delta t + \Delta t\) from Eqs. (13) and (14), the incremental frictional forces are expressed as

\[ \Delta Q_x = \Delta Q_x^{+\Delta t} \cdot \frac{x_t^{+\Delta t}}{y_t^{+\Delta t}} - \Delta Q_x \\
\Delta Q_y = \Delta Q_y^{+\Delta t} \cdot \frac{y_t^{+\Delta t}}{x_t^{+\Delta t}} - \Delta Q_y \]

(16)
(17)

In order to solve the incremental matrix Eq. (12), the incremental frictional forces \(\Delta Q_x\) and \(\Delta Q_y\) should be known at any time interval. The incremental frictional forces involve the system velocities at time \(t + \Delta t\) by Eqs. (16) and (17) which in turn depend on the incremental displacements \(\Delta x_b\) and \(\Delta y_b\) at the current time step. As a result, an iterative procedure is required to obtain the required incremental solution. The steps of the procedure considered are as follows:

1. Assume \(\Delta Q_x = \Delta Q_y = 0\) for iteration, \(i = 1\) in the Eqs. (16) and (17) and solve Eq. (12) for \(\Delta x_b\) and \(\Delta y_b\).
2. Calculate the incremental velocity \(\Delta x_b\) and \(\Delta y_b\) using the \(\Delta x_b\) and \(\Delta y_b\).
3. Calculate the velocities at time \(t + \Delta t\) using incremental velocities (i.e., \(x_t = x_t^{+\Delta t} + \Delta x_b\) and \(y_t = y_t^{+\Delta t} + \Delta y_b\)) and compute the revised incremental frictional forces \(\Delta Q_x\) and \(\Delta Q_y\) from Eqs. (16) and (17), respectively.
4. Iterate further, until the following convergence criteria are satisfied for both incremental frictional forces i.e.

\[ \left|\frac{\Delta Q_x^{i+1} - \Delta Q_x^i}{\Delta Q_x^i}\right| \leq \epsilon \\
\left|\frac{\Delta Q_y^{i+1} - \Delta Q_y^i}{\Delta Q_y^i}\right| \leq \epsilon \]

(19)

where \(\epsilon\) is a small threshold parameter. The superscript to the incremental forces denotes the iteration number.

When the convergence criteria are satisfied, the velocity of the sliding structure at time \(t + \Delta t\) is calculated using incremental velocity. In order to avoid the unbalance forces, the acceleration of the system at time \(t + \Delta t\) is evaluated directly from the equilibrium of system Eq. (9).

The number of iterations in each time step is taken as 10 to determine the incremental frictional forces at the sliding support.

The base shear is a measure of the hydrodynamic forces generated in the tank which is directly proportional to the earthquake forces exerted in the tank. Therefore, the effectiveness of base isolation is measured in terms of reduction of the base shear generated in the tank during earthquake. The base shear is directly proportional to the axial compressive forces induced in the cylindrical tank wall which causes the buckling (Malhotra, 1997b). The base shear generated in \(x\) and \(y\)-directions of the tank are expressed by

\[ F_{bxy} = m_t u_{xy} \cdot m_t u_{xy} + (m_t + m_b) u_{xy} \]
(20)

for non isolated

\[ F_{bxy} = m_t u_{xy} + m_t u_{xy} + m_t u_{xy} + 2m_t u_{xy} \]
(21)

for isolated
6. System Parameters

The period, $T_s$, and damping, $\xi_s$, of the tower structure are defined on the basis of a single-degree-of-freedom concept as

$$T_s = \frac{2\pi\sqrt{MK_s}}{\omega_s}$$

$$\xi_s = \frac{c_s}{2M\omega_s}$$

where $\omega_s$ (i.e. $2\pi / T_s$) the frequency of tower structure. Similarly, the isolation period, $T_b$, and the damping ratio, $\xi_b$, are computed using Eqs. (22) and (23) by substituting isolation stiffness, $k_b$, and frequency $\omega_b$, respectively.

7. Numerical Study

Seismic response of liquid storage slender and broad steel tanks isolated by the resilient-friction base isolator, R-FBI, is investigated. The two tank models considered for this study are: isolated model-I (isolation at base) and isolated model-II (isolation at top). In this study only fundamental mode of each of sloshing, impulsive and rigid masses is considered. The properties of the sliding system (such as stiffness, damping and friction) are kept the same in both x- and y-directions of the system. As a result, the sliding isolation system can be completely defined by the three parameters namely the period of isolation, $T_b$, the damping ratios, $\xi_b$, and the coefficient of friction, $\mu_{\text{max}}$. However, other tank parameters such as damping ratio of sloshing mass ($\xi_c$) and the impulsive mass ($\xi_i$) are taken as 0.5 percent and 2 percent, respectively (Malhotra, 1997b). The tank wall is considered of steel with modulus of elasticity, $E = 200$ kN/m$^2$ and mass density, $\rho_s = 7,900$ kg/m$^3$.

Figure 3 illustrates the displacement and acceleration spectra of Imperial Valley, 1940 earthquake. The two orthogonal components of the earthquake ground motion are S90W and S00E, applied in the x-direction and y-direction, respectively. The response quantities of interest in both x- and y-directions of the tank are: base shear ($F_{bx}$, $F_{by}$), displacements of sloshing mass ($x_c$, $y_c$), displacement of impulsive mass ($x_i$, $y_i$), tower drift ($x_s$, $y_s$) and displacements of sliding system ($x_b$, $y_b$). It was observed that the impulsive displacement is very small, therefore, not indicated (Shrimali and Jangid, 2002; Kim and Lee, 1993). For comparative and detailed parametric study two different types of tanks, namely the broad and slender tanks are considered. The properties of these tanks are: (i) aspect ratio ($S$) for slender and broad tanks is 1.85 and 0.6, respectively; (ii) the height, $H$, of water filled in the slender and broad tanks is 5 m; (iii) the natural frequencies of sloshing mass and impulsive mass for the broad and slender tank are 0.123, 3.944 Hz and 0.273, 5.963 Hz; and (iv) the ratio of tank wall thickness to its radius ($t_i/R$) is taken 0.004 for both the tanks. Note that the same value of $t_i/R = 0.004$ is used in deriving the

Figure 3. Displacement and acceleration spectra of Imperial Valley, 1940 earthquake (a) x-direction component and (b) y-direction component.

Figure 4. Time variation of response of slender tank in x-direction under Imperial Valley, 1940 earthquake ($T_b = 2$ s, $\mu_{\text{max}} = 0.05$, $\xi_s = 0.1$ and $T_s = 1$ s).
Eqs. (1-4) and (10). The base shear of the tank is normalized by the effective weight of the tank, $W$ (i.e. $W - M g$).

The time variation of base shear and relative displacements of the sloshing mass, tower drift and base mass isolated by the R-FBI system for slender and broad tanks (for isolated model-I) is shown in Figs. 4, 5 and 6, 7; for x- and y- directions, respectively. The isolation parameters considered are: $T_b = 2s$, $\mu_{\text{max}} = 0.05$, $\xi_b = 0.1$ and $T_s = 1s$.

It is found that due to isolation of the tanks there is significant reduction in the base shear and tower drift indicates effectiveness of the R-FBI system. On the other hand, the sloshing displacement of slender tank is reduced and both interaction and no-interaction conditions give nearly same value. However, in broad tank the no-interaction condition predict higher sloshing displacement. This is due to the fact that the period of sloshing mass is 3.66 sec which is well separated from period of the isolation systems hence isolation does not have significant effect on sloshing displacement. The peak bearing displacements for interaction and without interaction conditions are: 7.9, 12.05 and 9.53, 9.87 cm in x- and y- directions of the slender tank, respectively. Similarly for the broad tank the corresponding displacements are: 6.94, 12.05 and 9.53, 9.87 cm which are quite less than that of the slender tank.

Further, the bearing displacement is found to be increased due to the interaction of the friction forces of the sliding system. This is due to fact that when the interaction is...
taken into consideration the system starts sliding at a relatively lower value of the frictional forces mobilized in the sliding system (refer Eq. (10)), as a result, the sliding displacement in the isolated system is increased. Thus, if the interaction of the frictional forces of the sliding system is ignored than the sliding displacements will be underestimated which can be crucial from the design point of view of the isolation system.

7.1. Effects of aspect ratio

In order to investigate the response of isolated tanks for a wide range of practical liquid storage tanks (with and without interaction), the response is plotted against aspect ratio, $S$ as shown in the Fig. 8. The model-II slightly predicts higher value of base shear and tower drift in comparison to model-I. The sloshing displacement after initial variation the model-I predict marginally higher value than the model-II. The bearing displacement in the model-I is comparatively less than the model-II. This indicates that the isolation system is more effective for model-I than model-II.

7.2. Effects of flexibility of tower

The above study is confined for fixed parameters of R-FBI system for isolated liquid storage tanks. However, it will be interesting to study the influence of isolation parameters (such as period, damping and friction coefficient) on the behaviour of isolated tanks. The variation of resultant base shear, $F_b$, (i.e. $\sqrt{F_{bx}^2 + F_{by}^2}$), sloshing displacement, $z_c$, tower drift, $z_s$ and bearing displacement, $z_b$ for both slender and broad tanks are plotted against the tower period, $T_s$ in Fig. 9. The figure indicates that the base shear decreases with increase of tower flexibility. Further, the interaction predicts slightly higher result in comparison to no-interaction case. The sloshing displacement with interaction in slender tank (model-I) is marginally more while in broad tank the model-II predict higher value. The bearing displacement...
for the model-II is more than model-I; however, the model-I with interaction condition predict higher response in comparison to no-interaction.

### 7.3. Effects of flexibility of isolation system

The influence of isolation period on response of both the tanks is shown in the Fig. 10. It is observed that as flexibility of the isolation system increases the base shear decreases and model-I with interaction give marginally higher response. This is because the increased flexibility transmits less acceleration, hence less base shear. There is no significant influence on sloshing displacement except in broad tank without interaction condition. The tower drift due to interaction predicts higher drift for the model-I. For model-II after initial decrease it increases implies that care should be taken to design the isolation system. The bearing displacement increases with increases of the time period, which is obvious. In slender tank the interaction predicts higher base displacement for model-I while for model-II both the conditions predict very close result.

### 7.4. Effects of isolation damping

Fig. 11 illustrates the variation of peak resultant seismic response of slender and broad tanks against the isolation damping, $\xi_b$. The figure indicates that the base shear initially decreases with increase of the damping and interaction condition predicts slightly higher response for the model-I in comparison to model-II. In slender tank sloshing displacement with interaction slightly higher value while in broad tank it is vice-versa. Further, the tower drift increases as isolation damping increases (for model-II after initial decrease), which is obvious because the increased damping transmits more acceleration to the
structure. The interaction condition predicts higher sloshing displacement for the model-I while for the model-II both the conditions predict very close result. The bearing displacement decreases as isolation damping increases. This suggests that appropriate value of damping should be selected in order to accommodate the base displacement within the limits with minimum base shear. This indicates an appropriate value of the isolation damping should be selected.

7.5 Effects of coefficient of friction

The effects of coefficient of friction, $\mu_{\text{max}}$ on the resultant response of isolated tanks are shown in the Fig. 12. It is observed that increased value of friction coefficient transmits more acceleration, hence more base shear. The sloshing displacement is not significantly influenced by the change of friction coefficient. However, increase in friction coefficient increases the tower drift and for model-I both the conditions give very close result while for model-II without interaction condition predicts marginally higher result. Further, the bearing displacement decreases as friction coefficient increases. This implies that care should be taken for proper design of the isolation system to choose a friction coefficient. Because higher friction coefficient transmits higher acceleration result in more base shear but lesser base displacement.

8. Conclusions

The response of liquid storage tanks supported on the resilient-friction base isolator (R-FBI) subjected to bi-directional earthquake ground motion is investigated considering fundamental mode of each of the lumped masses. The interactions are duly incorporated in the governing equations of motion of the system. The response of the isolated system under the real earthquake ground motion is analyzed to investigate the performance of the sliding system for seismic isolation of tanks.
the trends of the results of present study, following conclusions may be drawn:

1. The R-FBI system is found to be quite effective in reducing the base shear and tower drift of the liquid storage tanks. However, the sloshing displacement of the tank is not significantly influenced due to isolation.

2. The isolated model-I is more effective in comparison to model-II to control the response of the liquid tanks.

3. The bi-directional interaction of frictional forces has significant effects on the response of isolated tanks. If these effects are ignored than the bearing displacement will be underestimated which can be crucial from the design point of view for model-I.

4. The isolation system is more effective for rigid type tower structure.

5. The value of friction coefficient and damping of the R-FBI system should be so selected to achieve minimum base shear with base displacement within permitted limits.

References


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Figure 12. Effect of friction coefficient on the peak resultant response of tanks ($T_b = 2s$, $\xi_b = 0.1$ and $T_s = 1s$).


