Earthquake Response of Liquid Storage Tanks with Sliding Systems

M.K. Shrimali[1] and R.S. Jangid[2]

1. Research Scholar, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai-400 076, India, email: rshrimli@civil.ittb.ac.in
2. Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai-400 076, India, email: rsjangid@civil.ittb.ac.in

ABSTRACT: *Earthquake response of liquid storage tanks isolated by the sliding systems is investigated under bi-directional earthquake motion (i.e. two horizontal components). The frictional force of sliding systems is modeled by two ways referred as conventional and hysteretic model. The continuous liquid mass is lumped as convective mass, impulsive mass and rigid mass. The corresponding stiffnesses associated with these lumped masses are worked out depending upon the properties of the tank wall and liquid mass. The governing equations of motion of the tank with sliding system are derived and solved by Newmark's step-by-step method with iterations. The frictional forces mobilized at the interface of the sliding system is assumed to be velocity independent and their interaction in two horizontal directions is duly considered. For comparative study the earthquake response of isolated liquid storage tank obtained by conventional model is compared with corresponding response obtained by hysteretic model. In order to measure the effectiveness of isolation system the earthquake response of isolated tank is also compared with non-isolated tank. A parametric study is also conducted to study the effects of aspect ratio of the tank on the effectiveness of seismic isolation of the liquid storage tanks. It is found that the sliding systems are quite effective in reducing the earthquake response of liquid storage tanks. In addition, the same earthquake response of liquid storage tanks is predicted by conventional and hysteretic model of the sliding system.*

Keywords: Liquid storage tank; Base isolation; Sliding system; Earthquake; Bi-directional excitation; Conventional model; Hysteretic model; Aspect ratio

1. Introduction

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 transmitted directly to the structure, and that 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 period of structural vibration beyond the energy containing period of earthquake ground motions. The other purpose of an isolation system is to provide an additional means of energy dissipation, thereby reducing the transmitted acceleration into the superstructure. The 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 earthquake-resistant design of buildings [1, 2]. A significant amount of the recent research in base isolation has focused on the use 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 [3]. More advanced devices involve pure-friction elements in combination with a restoring force. The restoring force in the system reduces the base displacements and brings back the system to its original position after an earthquake. Some of the commonly proposed sliding systems with restoring force include the resilient-friction base isolator (*F*-*FBI*) system [4], the friction pendulum system (*EPS*) [5], Electricite de France system (*EDF*) [6] and elliptical rolling rods [7]. 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 base displacements [4, 8]. In addition, the sliding systems are also less sensitive to the effects of torsional coupling in asymmetric base-isolated buildings [9].

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 industrial and strategic use. Kim and Lee [10] experimentally investigated the earthquake performance of liquid storage tank isolated by the elastomeric bearings and found that such system is quite effective in reducing the dynamic response. Malhotra [11, 12], Chalhoub and Kelly [13], and Shrimali and Jangid [14] studied the earthquake response of isolated liquid storage tanks and observed that isolation is effective in reducing the earthquake forces. It is to be noted that in all the above studies the elastomeric bearings has been used and there is a need to study the performance of sliding systems for seismic isolation of liquid storage tanks.

In this paper, response of liquid storage tanks isolated by the sliding systems under bi-direction excitation with interaction effect is investigated. The specific objectives of the present study may be summarized as

i To investigate the effectiveness of sliding systems for seismic isolation of liquid storage tanks,

ii To compare the earthquake response of isolated liquid storage tanks obtained by conventional and hysteretic model of the sliding systems for ascertaining the suitability of the models, and

iii To study the influence of aspect ratio of the tank on the effectiveness of sliding system for earthquake design of liquid storage tanks.

2. Model of Liquid Storage Tank and the Sliding Systems

The model of a liquid storage tank mounted on the sliding system is shown in Figure (1). The sliding system is installed between the base and the foundation of the tank. The tank is modelled by the lumped mass model suggested by Housner [15], Rosenblueth and Newmark [16] and Haroun [18].

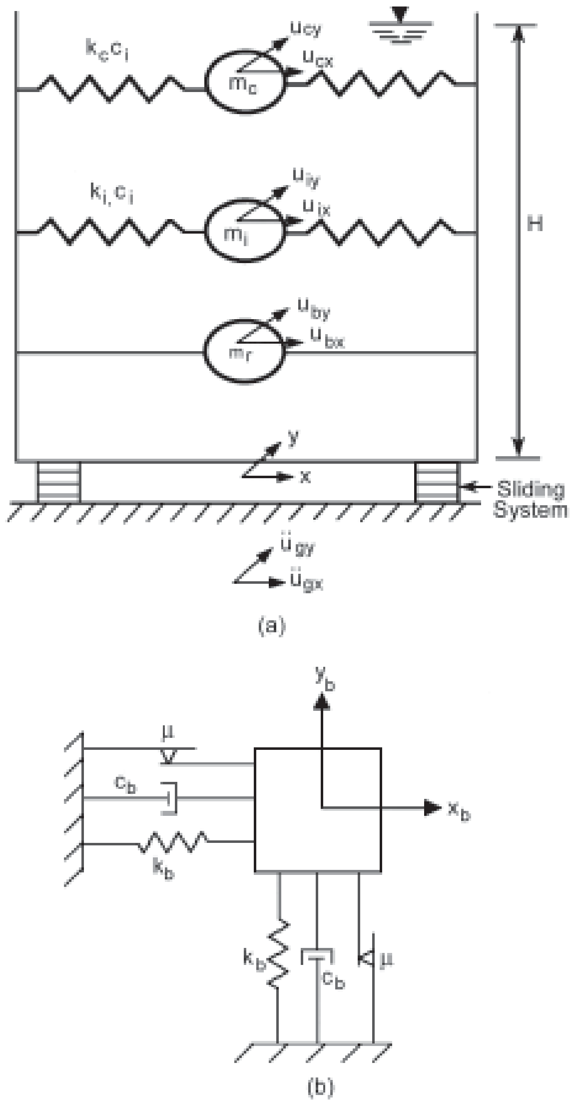

Figure 1. Model of a liquid storage tank mounted on sliding system.

The system has six-degrees-of-freedom under bi-directional excitation, two-degree-of-freedom of each lumped mass in two horizontal x and y-directions, respectively. These degree-of-freedom are denoted by $(u_{cx}, u_{cy}), (u_{ix}, u_{iy})$ and (u_{bx}, u_{by}) which denote the absolute displacement of convective, impulsive and rigid masses in x and y-directions, respectively. The various assumptions made for the system under consideration are as follows:

1. The continuous liquid mass of tank is lumped and referred as convective mass, m_c, impulsive mass, m_i, and rigid mass, m_r. The wall of the tank is considered as deformable and self-weight of tank is very small in comparison to effective weight of the liquid, hence neglected.
2. The convective and impulsive masses are connected to the tank wall by corresponding equivalent spring having stiffness k_c and k_i, respectively, are computed using liquid and tank properties.
3. The damping constant associated with the movement of convective and impulsive masses are expressed by the assumed damping ratios.
4. The sliding system is isotropic i.e. there is the same coefficient of friction in two orthogonal directions of the motion in the horizontal plane.
5. The earthquake response of the system is obtained by duly considering the interaction of the frictional forces mobilized at the interface of the sliding system.
6. Restoring force provided by the sliding systems is considered to be linear (i.e. proportional to relative displacement) and additional damping (other than friction) is assumed as viscous damping, see Figure (1b).
7. The friction coefficient of sliding system is assumed to be independent on the relative velocity of superstructure at the sliding interface. This is based on the findings that such effects do not have noticeable effects on the peak response of the isolated structural system [8, 17].

The effective masses referred as m_c, m_i and m_r are defined in terms of liquid mass m which depends on the tank parameters such as liquid height H, radius, R and average thickness of tank wall are expressed [18] as

$$Y_c = 1.01327 - 0.87578\,S + 0.35708\,S^2 - 0.06692\,S^3 + 0.00439\,S^4 \tag{1}$$

$$Y_i = -0.15467 + 1.21716\,S - 0.62839\,S^2 + 0.14434\,S^3 - 0.0125\,S^4 \tag{2}$$

$$Y_r = -0.01599 + 0.86356S - 0.30941S^2 + 0.04083S^3 \tag{3}$$

where $S = H/R$ is the aspect ratio (i.e. ratio the liquid height to radius of the tank) and Y_c, Y_i, and Y_r are the mass ratios defined as

$$Y_c = \frac{m_c}{m} \tag{4}$$

$$Y_i = \frac{m_i}{m} \tag{5}$$

$$Y_r = \frac{m_r}{m} \tag{6}$$

$$m = \pi R^2 H \rho_w \tag{7}$$

The natural frequencies of sloshing mass, ω_c and impulsive mass, ω_i are given by following expressions as

$$\omega_i = \frac{P}{H}\sqrt{\frac{E}{\rho_s}} \tag{8}$$

$$\omega_c = \sqrt{1.84\left(\frac{g}{R}\right) tanh\left(1.84\frac{H}{R}\right)} \tag{9}$$

where E and ρ_s are the modulus of elasticity and of tank wall, respectively; g is the acceleration due to gravity; and P is a dimensionless parameter expressed as

$$P = 0.037085 + 0.084302S - 0.05088S^2 + 0.012523\,S^3 - 0.0012\,S^4 \tag{10}$$

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

$$k_c = m_c \omega_c^2$$

$$k_i = m_i \omega_i^2$$

$$c_c = 2\,\xi_c m_c \omega_c$$

$$c_i = 2\,\xi_i m_i \omega_i \tag{14}$$

where ξ_c and ξ_i are damping ratio of convective mass and impulsive mass, respectively.

3. Governing Equations of Motion

The equations of motion of isolated liquid storage tank subjected to earthquake ground motion are expressed in the matrix form as

$$[m]\{\ddot{z}\} + [c]\{\dot{z}\} + [k]\{z\} + \{F\} = -[m][r]\{\ddot{u}_g\} \tag{15}$$

where $\{z\} = \{x_c, x_i, x_b, y_c, y_i, y_b\}^T$ and $\{F\} = \{0, 0, F_x, 0, 0, F_y\}^T$ 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 convective mass relative to bearing displacements in x and y-directions, respectively; and $y_i = u_{iy} - u_{by}$ are the displacements of the impulsive mass relative to bearing displacements in x and y-directions, respectively; and $u_{by} - u_{gy}$ 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 matrix of the system, respectively; [r] is the influence coefficient matrix; is the earthquake ground acceleration vector; $(\ddot{u}_{gx}, \ddot{u}_{gy})$ and (F_x and F_y) are the ground accelerations and the frictional forces in the x and y-directions of the system, respectively; and T denotes the transpose.

The stiffness and damping of the sliding system are designed in such a way to provide specified value of the parameters namely the isolation period (T_b) and the damping ratio (ξ_b) expressed as

$$T_b = 2\pi\sqrt{\frac{M}{k_b}} \tag{16}$$

$$\xi_b = \frac{c_b}{2M\omega_b} \tag{17}$$

where M is the effective mass of the tank (i.e. $m_c + m_i + m_r$); c_b and k_b are isolation damping and horizontal stiffness; $\omega_b = 2\pi/T_b$ is the isolation frequency.

The limiting value of the frictional force, F_s to which the sliding system can be subjected (before sliding) is expressed as

$$F_s = \mu M g \tag{18}$$

where μ is the friction coefficient of the sliding system.

4. Modeling of Frictional Force

The frictional force in sliding system is modeled by two models referred as conventional model and hysteretic model. The conventional model is a discontinuous one and number of stick-slide conditions renders different number of equations to be solved and checked at every stage while the hysteretic model is continuous and the required continuity is automatically maintained by the hysteretic displacement components.

4.1. Conventional Model

In the conventional model, the frictional force in the isolation system is evaluated by considering the equilibrium of the base (during the non-sliding phase) and the limiting value of frictional force (during sliding phase). This model had been extensively used in the past by many researchers for evaluation of the dynamic response of structures with sliding systems [17, 19, 20, 21]. The system remains in the non-sliding phase $= \ddot{y}_b = 0)$ and ($\dot{x}_b = \dot{y}_b = 0$) if the frictional force mobilized at the interface of sliding system is less than the limiting frictional force (i.e. $\sqrt{F_x^2 + F_y^2} < F_s$). During the non-sliding phase, the equations of motion of the convective and impulsive mass are integrated and the corresponding frictional force in x and y-directions, respectively, is evaluated by

$$F_x = -(m_c \ddot{x}_c + m_i \ddot{x}_i + M\ddot{x}_b + k_b x_b + M\ddot{u}_{gx}) \tag{19}$$

$$F_y = -(m_c \ddot{y}_c + m_i \dot{y}_i + M\ddot{y}_b + k_b y_b + M\ddot{u}_{gy}) \tag{20}$$

The system starts sliding and $\dot{x}_b \neq \dot{y}_b \neq 0$) as soon as the frictional force attains the limiting frictional force (i.e. $F_x^2 + F_y^2 = F_s^2$). This indicates a circular interaction between the frictional forces mobilized at the interface of the sliding system as shown in Figure (2a). 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 isolators are coupled during the sliding phases due to interaction between the frictional forces.

Whenever the relative velocity of the base mass becomes zero (i.e. $\dot{x}_b = \dot{y}_b = 0$), the phase of the motion is to be checked in order to determine whether the system remains in the sliding phase or sticks to the foundation. Thus, the conventional model is a discontinuous model in which different set of equations of motion are to be solved for evaluating the earthquake response of the isolated liquid storage tank depending upon the phase of motion.

4.2. Hysteretic Model

The hysteretic model is a continuous model of the frictional force proposed by Constantinou et al [22] using the Park et al [23]. The frictional forces mobilized in the sliding system is expressed by

$$F_x = F_s Z_x \tag{21}$$

$$F_y = F_s Z_y \tag{22}$$

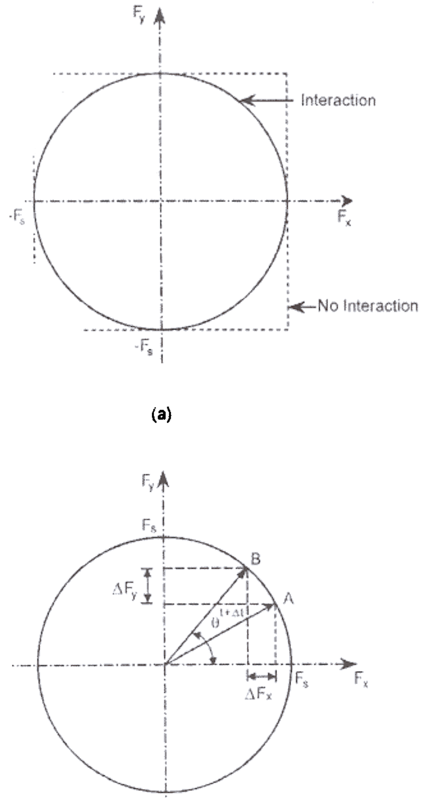

Figure 2. Interaction and incremental frictional forces in two orthogonal direction of sliding systems.

where F_s is the limiting frictional force expressed by Eq. (18); and non-dimensional hysteretic displacements Z_x and Z_y, which represent non-linear behaviour of frictional forces, are obtained by following expression as

$$q\begin{Bmatrix}\dot{Z}_x\\ \dot{Z}_y\end{Bmatrix}=\begin{bmatrix}A-\beta\, sgn(\dot{x}_b)\left|Z_x\right|Z_x-\tau Z_x^2 & -\beta\, sgn(\dot{y}_b)\left|Z_y\right|Z_x-\tau Z_x Z_y\\ -\beta\, sgn(\dot{x}_b)\left|Z_x\right|Z_y-\tau Z_x Z_y & A-\beta\, sgn(\dot{y}_b)\left|Z_y\right|Z_y-\tau Z_x^2\end{bmatrix}\begin{Bmatrix}\dot{x}_b\\ \dot{y}_b\end{Bmatrix} \tag{23}$$

where q is the yield displacement, and β, τ and A are non-dimensional parameters which control the shape of hysteresis loop. The parameters are selected such that the predicted response from the model matches with experimental results. The interaction between the frictional forces in the sliding system is due to coupling through the off diagonal terms of matrix in the Eq. (23) in two horizontal directions and no interaction condition is obtained by replacing the off-diagonal coupling terms by zero. The parameters β, τ and A control the shape of the loop and are selected such that to provide a rigid-plastic shape (i.e. typical Coulomb-friction behaviour). The recommended values for the above parameters are: $q = 0.25mm, A = 1$, $\beta = 0.9$ and $\tau = 0.1$. The hysteretic displacement components, Z_x and Z_y are bounded by its peak values of ± 1 to account for the conditions of sliding and non-sliding phases. Thus, the hysteretic model is a continuous model in which the system is analyzed for entire degrees-of-freedom for all phases of motion.

5. Solution of Equations of Motion

The frictional force mobilized in the sliding system is non-linear function f the displacement and velocity of the system, as a result, an interactive incremental solution procedure is required for solution of equations of motion. The Newmark's step-by-step method assuming linear variation of acceleration over a small time interval is chosen for evaluating the response of the system. The governing incremental matrix equation for evaluation can finally be written in the matrix form as

$$\left[k_{eff}\right]\{\Delta z\}=\{P_{eff}\}-\{\Delta F\}$$

$$\left[k_{eff}\right]=a_0[m]+b_0[c]+[k] \tag{25}$$

$$\{P_{eff}\}=-[m]\{r\}\{\Delta\ddot{u}_g\}-[m]\left(a_1\{\dot{z}\}^t+a_2\{\ddot{z}\}^t\right)-[c]\left(b_1\{\dot{z}\}^t+b_2\{\ddot{z}\}^t\right)$$

where $a_0=\dfrac{6}{\Delta t^2}; a_1=-\dfrac{6}{\Delta t}; a_2=-3; b_1=-3; b_2=-\dfrac{\Delta t}{2}$; $\{k_{eff}\}$ is the effectiveness stiffness matrix; $\{\Delta z\}=\{\Delta x_c, \Delta x_i, \Delta x_b, \Delta y_c, \Delta y_i, \Delta y_b\}^T$ is the incremental displacement $\{\Delta F\}=\{0, 0, \Delta F_x, 0, 0, \Delta F_y\}^T$ vector is the incremental frictional force vector; $\{P_{eff}\}$ is the effective excitation vector; ΔF_x and ΔF_y are incremental frictional forces in x and y-directions, respectively.

In order to find the incremental frictional forces developed in the conventional model, consider that the frictional forces moves from point A to B as shown in the Figure (2b) and the incremental frictional forces in the x and y-direction are expressed as

$$\Delta F_x = F_s cos\left(\theta^{t+\Delta t}\right)-F_x^t$$

$$\Delta F_y = F_s sin\left(\theta^{t+\Delta t}\right)-F_y^t$$

Since the frictional forces opposes the motion of the system and will be action in the direction of sliding. As a result, the direction of sliding or the angle $\theta^{t+\Delta t}$ will be equal to expressed by $tan^{-1}\left(\dot{y}_b^{t+\Delta t}/\dot{x}_b^{t+\Delta t}\right)$.

Substituting for angle $\theta^{t+\Delta t}$ in Eqs. (27) and (28), the incremental frictional forces [3] are expressed as

$$\Delta F_x = F_s \frac{\dot{x}_b^{t+\Delta t}}{\sqrt{(\dot{x}_b^{t+\Delta t})^2 + (\dot{y}_b^{t+\Delta t})^2}} - F_x^t \quad (29)$$

$$\Delta F_y = F_s \frac{\dot{y}_b^{t+\Delta t}}{\sqrt{(\dot{x}_b^{t+\Delta t})^2 + (\dot{y}_b^{t+\Delta t})^2}} - F_y^t \quad (30)$$

For the hysteretic model, the incremental frictional forces are computed from Eqs. (21) and (22) by the following expressions

$$\Delta F_x = F_s \Delta Z_x \quad (31)$$

$$\Delta F_y = F_s \Delta Z_y \quad (32)$$

in which ΔZ_x and ΔZ_y are the incremental hysteretic displacement component in x- and y-direction of the system. These incremental hysteretic displacement components are obtained by solving the first order coupled differential equations using the Rung-Kutta method.

Since the incremental frictional force in both models depend on the sliding velocity at time $t+\Delta t$ (i.e. $\dot{x}_b^{t+\Delta t}$ and $\dot{y}_b^{t+\Delta t}$). As a result, an iterative procedure is to be followed to solve the incremental equations of motion. The response of the system is obtained initially with ΔF_x and ΔF_y are assumed equal to zero and revised for next iteration depending upon the sliding velocity. This iterative solution procedure is repeated until the following convergence criteria are satisfied

$$\frac{\left|(\Delta F_x)^{j+1}\right| - \left|(\Delta F_x)^{j}\right|}{\left|(\Delta F_x)^{j}\right|} \le \varepsilon \quad (33)$$

$$\frac{\left|(\Delta F_y)^{j+1}\right| - \left|(\Delta F_y)^{j}\right|}{\left|(\Delta F_y)^{j}\right|} \le \varepsilon \quad (34)$$

where ε is a small threshold parameter. The superscript to the incremental frictional force denotes the iteration number.

When the convergence criteria are satisfied, the velocities in x and y- directions of the sliding structure at time $t+\Delta t$ are calculated using the corresponding incremental velocity. In order to avoid the unbalance forces, the acceleration of the system in x and y- directions at time $t+\Delta t$ are evaluated directly from the equilibrium of system Eq. (15). The response of the sliding structures is quite sensitive in conventional model to the time interval, Δt and initial conditions at the beginning of sliding and non-sliding phases. The number of iterations in each time step is taken as 10 to determine the incremental frictional forces at the sliding support.

6. Numerical Study

The earthquake response of liquid storage tank isolated by the sliding system is investigated. Three types of commonly used sliding base isolation systems i.e. the pure-friction (*P-F*) system, the friction pendulum system (*FPS*) and the resilient-friction base isolator (*R-FBI*) are considered for the present study. The parameters of *P-F*, *FPS* and *R-FBI* systems considered are ($\mu = 0.1$), ($T_b = 2sec$ and $\mu = 0.05$) and ($T_b = 4sec$, $\xi_b = 0.1$ and $\mu = 0.04$), respectively which are typically recommended for these systems in the past. However, other tank parameters such as damping ratio of convective mass (ξ_c) and the impulsive mass (ξ_i) are taken as 0.5 percent and 2 percent, respectively and the tanks with steel wall the modulus of elasticity is taken as E = 200*MPa* and the mass density, $\rho_s = 7{,}900 kg/m^3$.

The earthquake response of isolated liquid storage tank is investigated under bi-directional excitation of Imperial Valley, 1940 and Kobe, 1995 earthquake ground motions. The peak ground acceleration (*PGA*) of two horizontal components *S* 90*W* and *S* 00*E* of the Imperial Valley are 0.21*g* and 0.34*g* applied in x and y- directions, respectively. Similarly, the peak *PGA* of the two com-ponents *N*90*E* and *N*00*E* of Kobe earthquake are 0.62*g* and 0.834*g* applied in x and y-directions, irrespectively. The response quantities of interest of the tank are base shear (F_{bx}, F_{by}); displacements of convective mass (x_c, y_c), impulsive mass (x_i, y_i) and isolation system (x_b, y_b). The earthquake response of the isolated tank is compared with corresponding response of the non-isolated tank in order to measure the effectiveness of the isolation system. The base shear of the tank is normalized by the effective weight of the tank, W (i.e. $W = M g$). The height, H of water filled in the tank is taken as 11.3*m* and the ratio of tank wall thickness to its radius is taken as 0.004. The earthquake response of tank isolated with three isolation system is investigated for different aspect ratio, S of the tank. For S = 1.85, which represent a slender tank, the natural frequencies of convective and impulsive mass for the tank are 0.273 and 5.963*Hz*, respectively.

The time variation of base shear and relative displacements of the convective mass, impulsive mass and base mass for the tank isolated by the *FPS* system is shown in Figures (3) and (4) for x- and y-directions, respectively, under the Imperial Valley, 1940 earthquake ground motion.The Figures indicate that due to isolation there is significant reduction in the base shear and impulsive displacement of the tank implying that the sliding system is quite effective in reducing the earthquake response of the tanks. Further, it is also observed from Figures (3) and (4) that the earthquake response obtained by conventional model and hysteretic model are the same indicating that both models predict the same trend and peak response of the liquid storage tanks. The percentage reduction in peak base shear in x-direction due to isolation of the tank by conventional and hysteretic models is 66.14 and 67.71, in *FPS* system, while in y-direction the corresponding reduction is 78.03 and 80.33. Similarly the percentage reduction in peak impulsive displacement in the isolated tank modeled by conventional and hysteretic models in x-direction is 71.79 and 71.79 while in y-direction the reduction is 86.08 and 85.54. These results indicate that the isolation is very effective for earthquake design of tanks and the peak base shear, peak impulsive displacement and peak sloshing displacement obtained by conventional model are very close to the corresponding result predicted by the hysteretic model in both the directions. The sloshing displacement of the tank due to isolation is slightly increased. 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 base displacement obtained by the conventional model and hysteretic model in x-direction is 6.19*cm* and 5.77*cm* while in y-direction the corresponding displacement is 5.12*cm* and 4.86*cm*. The above analysis shows that even the peak base displacement predicted by conventional and hysteretic models is very close to each other. Similar type of observation were made for the response of the tanks with *P-F* and *R-FBI* systems.

In Figure (5), variation of function force of the tank isolated by *FPS* system is plotted against the base displacement for both models under Imperial Valley, 1940 earthquake ground motion. The figure indicates that there is same variation of the frictional force obtained from the two models in both x and y-directions. In addition, the frictional forces of the sliding system are coupled in two directions. Further, it has been observed that the computational time required for the hysteretic model is significantly more in comparison to the conventional model (about 10 times). This is due to the fact that a very small time

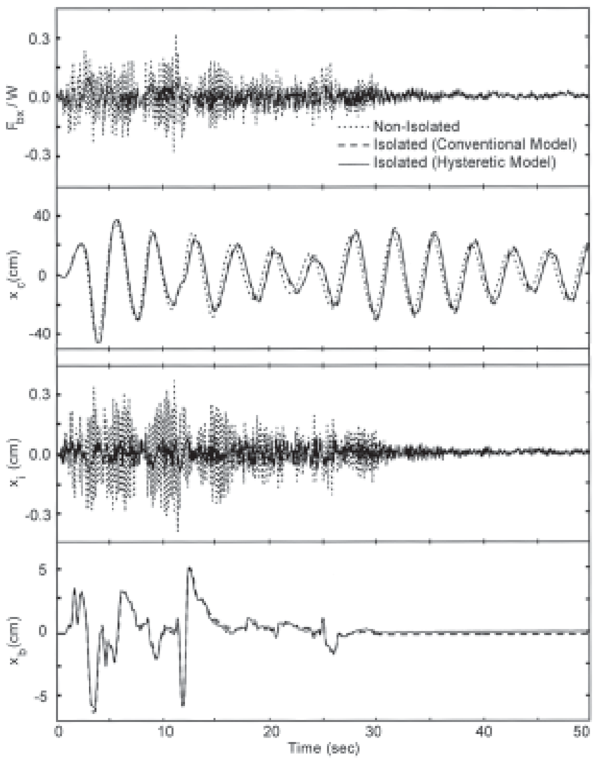

Figure 3. Time variation of response of liquid storage tank in x-direction isolated by the FPS system under Imperial Valley, 1940 earthquake (S = 1.85).

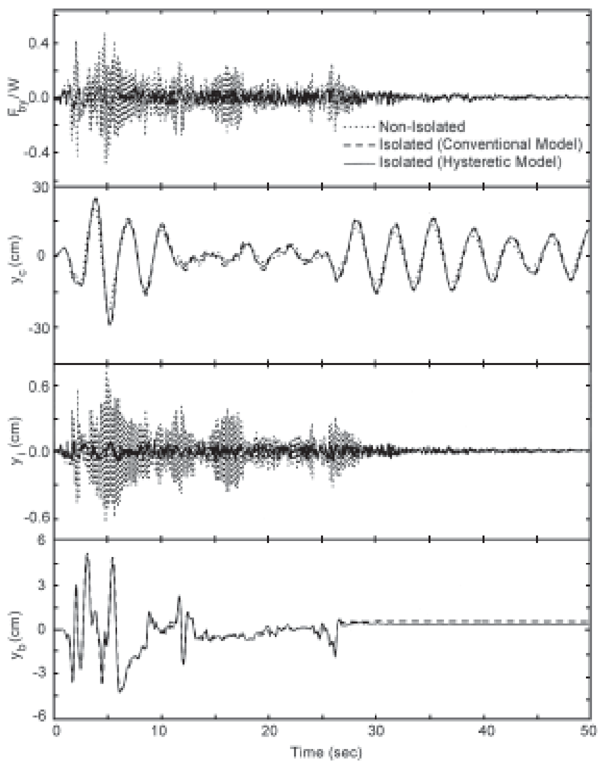

Figure 4. Time variation of response of liquid storage tank in y-direction isolated by the FPS system under Imperial Valley, 1940 earthquake (S = 1.85).

step is required to predict the rigid-plastic behaviour of the frictional force in the sliding system with hysteretic mode. Thus, the conventional model of the sliding system is computationally more efficient in comparison to hysteretic model.

The effects of aspect ratio of the tank, *S*, on the peak earthquake response of isolated and non-isolated tank is shown in Figures (6), (7), (8) and (9) for Imperial Valley and Kobe earthquake motions, respectively. The response in x and y-directions of the system is shown for both models of the frictional force and three isolation systems. It is observed that the base shear and impulsive displacement due to isolation are considerably reduced for entire range of

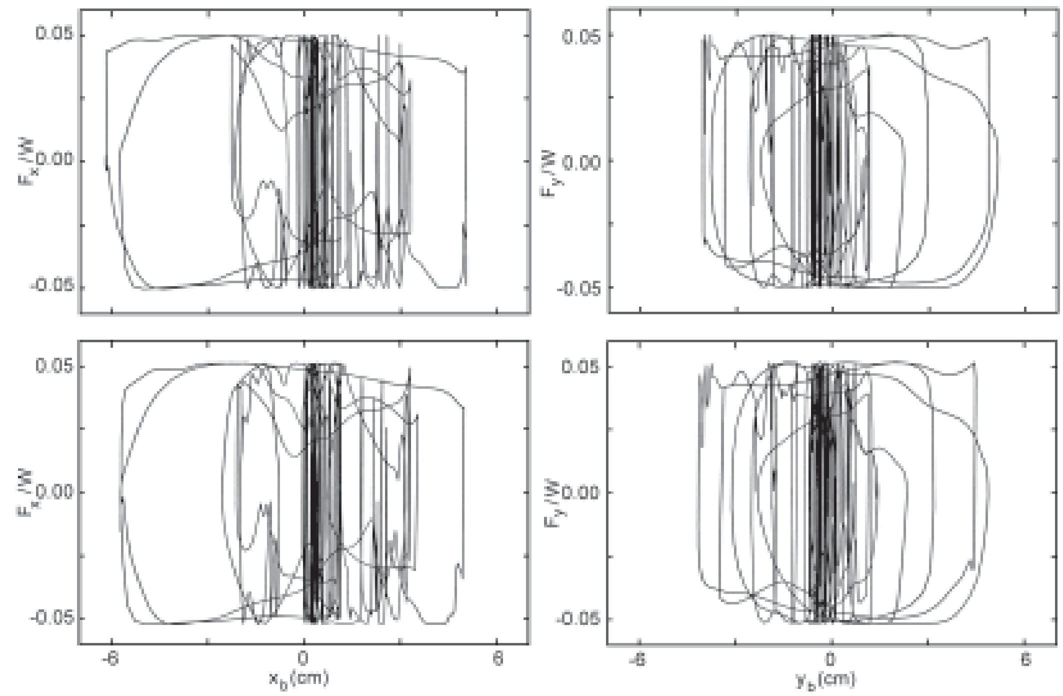

Figure 5. Comparison of frictional force loop for conventional and hysteretic models isolated by FPS in x and y directions (S = 1.85).

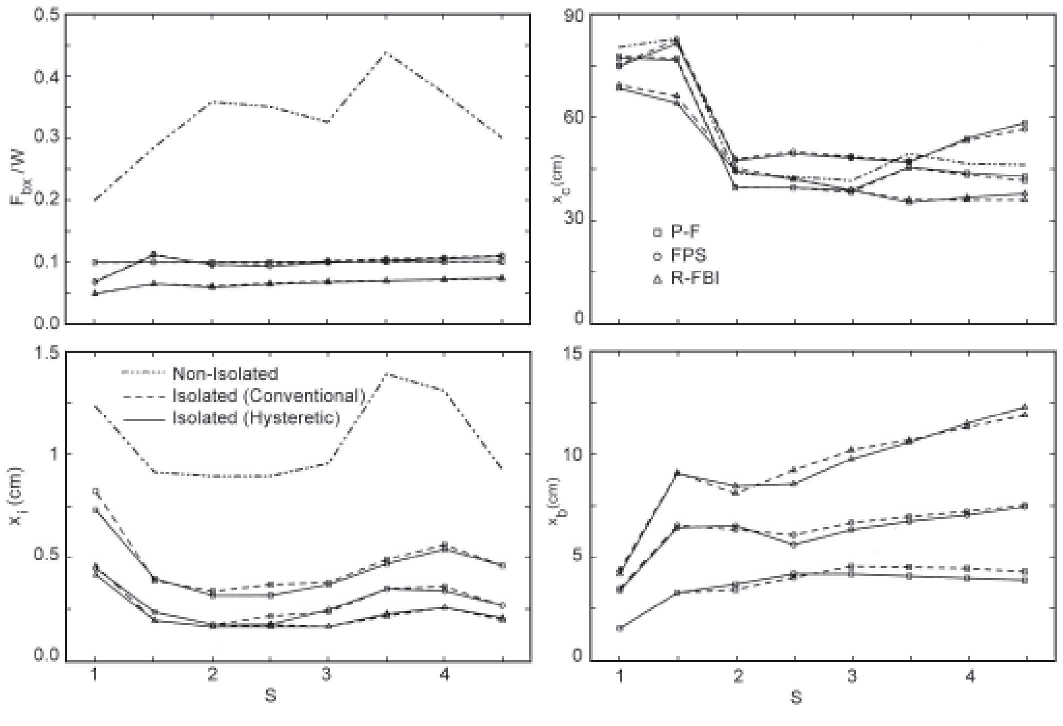

Figure 6. Effects of aspect ratio on the earthquake response in x-direction of isolated liquid storage tank under Imperial Valley, 1940 earthquake.

aspect ratio considered (0.5-4) under the earthquake ground motions. The reduction in base shear is relatively more for higher aspect ratio implying that the sliding systems are more effective for slender tanks in comparison to broad tanks. The base shear, impulsive displacement, sloshing displacement and base displacement of isolated tanks predicted by the conventional model closely matches with the corresponding response by hysteretic model in both the directions. However, the difference in the response between two models is relatively more for the *P-F* system as compared to the *FPS* and *R-FBI* systems.

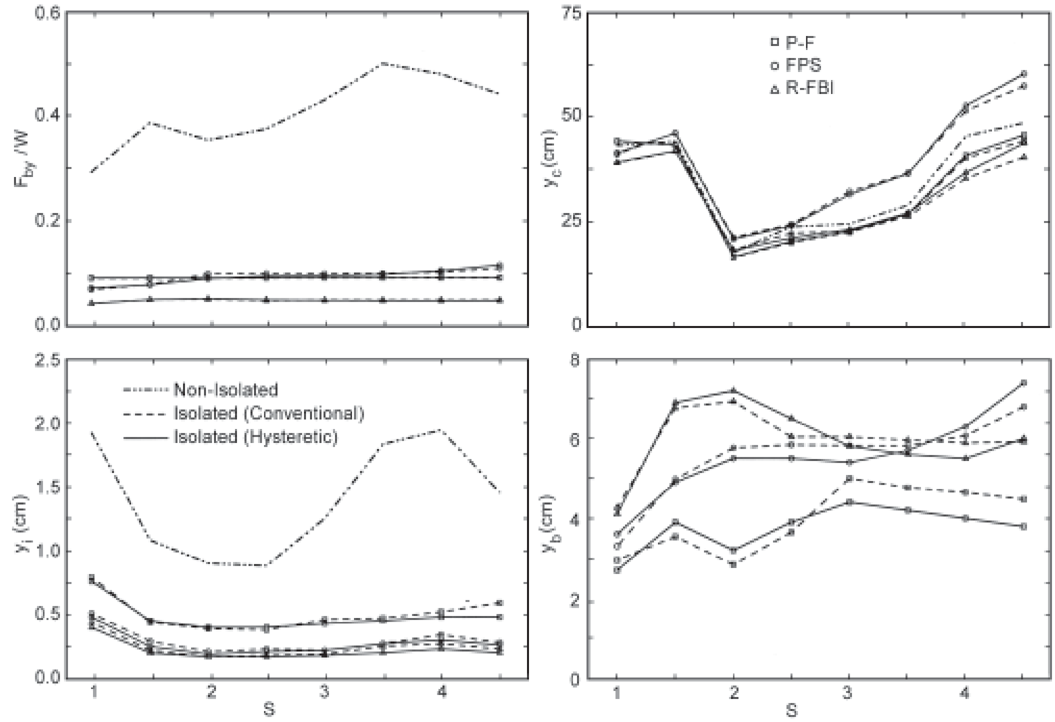

Figure 7. Effects of aspect ratio on the earthquake response in y-direction of isolated liquid storage tank under Imperial Valley, 1940 earthquake.

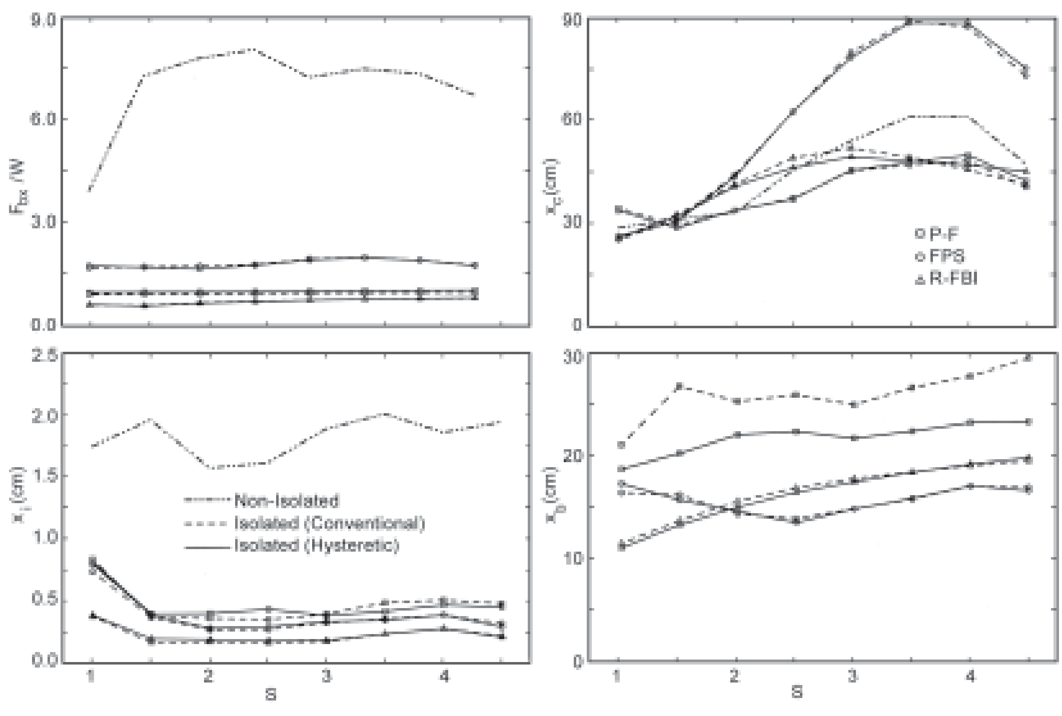

Figure 8. Effects of aspect ratio on the earthquake response in x-direction of isolated liquid storage tank under Kobe, 1995 earthquake.

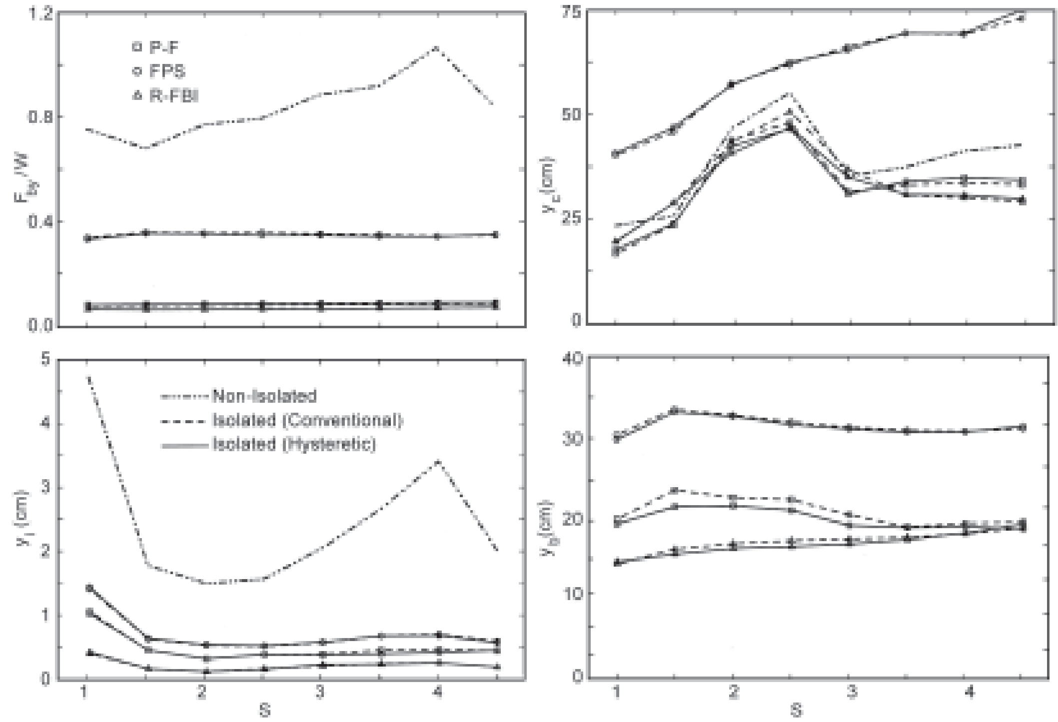

Figure 9. Effects of aspect ratio on the earthquake response in y-direction of isolated liquid storage tank under Kobe, 1995 earthquake.

7. Conclusions

The earthquake response of the liquid storage tank supported on the sliding systems subjected to two horizontal components of real earthquake ground motions is investigated. The frictional force of the sliding system is expressed by two models referred as conventional and hysteretic model. The response of the isolated tank system using both models under the recorded earthquake ground motions is analyzed to investigate the performance of sliding systems for seismic isolation of tanks. From the trends of the results of present study, following conclusions can be drawn:

- The sliding systems are found to be quite effective in reducing the base shear and impulsive displacement of the liquid storage tanks.
- The sloshing displacement of the tank is not much influenced due to isolation of tank by the sliding systems. However, under certain conditions it may be increased by seismic isolation depending upon the characteristics of earthquake motion and properties of tank and sliding system.
- The reduction in base shear is relatively more for higher aspect ratio implying that the sliding systems are more effective for slender tanks in comparison to broad tanks.
- The peak earthquake response such as base shear, impulsive, sloshing and base displacements predicted by the conventional and hysteretic model of fractional forces of the sliding system closely matches.
- The difference in the response of isolated tank (especially the sliding displacement between conventional and hysteretic models is found to be relatively more for the *P-F* system as compared to *FPs* and *R-FBI* systems.
- The conventional model is found to be computationally more efficient in comparison to hysteretic model for seismic analysis of liquid storage tanks with sliding systems.

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