

Comparison of base-isolated liquid storage tank models under bi-directional earthquakes

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ABSTRACT

Seismic response of ground supported base-isolated liquid storage tanks are evaluated under bi-directional earthquakes. The base-isolated liquid storage tanks are modeled using mechanical analogs with two and three lumped masses (Model 1 and Model 2). Two types of isolation systems, such as sliding system and elastomeric system, are considered for the present study. The isolation systems are modeled using Wen's equation for hysteretic isolation systems. Response of base-isolated liquid storage tanks, evaluated through two different modeling approaches, is compared. Both the models predict similar sloshing displacement. The effect of interaction between the mutually perpendicular seismic responses of the isolator is investigated for both the models. It is observed that interaction affects the peak seismic response of the base-isolated liquid storage tanks significantly, under the bi-directional earthquake components.

Keywords: Base Isolation; Bi-Directional; Earthquake; Interaction; Liquid; Sloshing; Tank

1. INTRODUCTION

Liquid storage tanks are one of the many important structures that demand greater safety measures against natural disaster like earthquake. Post failure consequences of industrial tanks sometimes trigger greater impact on human life through fire, chemical contamination, nuclear radiation etc. Besides these, water storage tanks are required to be maintained functional to serve the society even after devastating earthquake. Hence, protection of liquid storage tanks against earthquake is very essential. The dynamic behavior of liquid containing structures cannot be estimated by the same approach

as for normal building structure, since the inside liquid influences its behavior largely. Therefore, appropriate modeling of the liquid storage tanks is essential for dynamic analysis and seismic response evaluation. Several research works reported in literature and guidelines in international codes and specifications are available for seismic analysis and design of liquid storage tanks [1-4]. Most of the design guidelines follow the lumped mass mechanical analog to model the cylindrical liquid storage tanks. A brief review of the international codes on seismic analysis of liquid storage tanks can be found in [5]. However, conventional design approach, without sophisticated vibration control devices, many times cannot provide sufficient protection against seismic forces.

Several researchers have reported the benefits of the passive vibration control strategy using base isolation technique, as an efficient seismic protection method of structures [6-9]. There are two broad categories of base isolation systems, which are in use throughout the world, such as sliding system and elastomeric bearing. Malhotra [10], Shrimali and Jangid [11] and many other researchers reported the use of base isolation for enhancing seismic performance of liquid storage tanks. Shrimali and Jangid [12] investigated the effect of seismic response interaction on the performance of base-isolated liquid storage tanks. However, they had only considered the sliding bearing as isolation system. Jadhav and Jangid [13] compared the performance of different isolation systems for seismic protection of liquid storage tanks. They had investigated the performance of liquid storage tanks under bi-directional near-fault earthquake. However, the effect of the interaction between the orthogonal hysteretic responses of the isolators was not studied.

In most of the above research works, the base-isolated liquid storage tank has been modeled using the mechanical analog proposed by Haroun and Housner [14]. This model considers the tank wall flexibility while calculating the seismic response. Another mechanical analog, proposed earlier by Housner [4], is also extensively

used for modeling of liquid storage tanks for dynamic analysis. The major difference of these two models is the number of lumped masses into which the liquid column is divided. Whereas, the two-mass model is convenient for designers to use due to ease, the three-mass model apparently predicts the seismic response more accurately. Hence, the choice of an appropriate modeling approach is crucial.

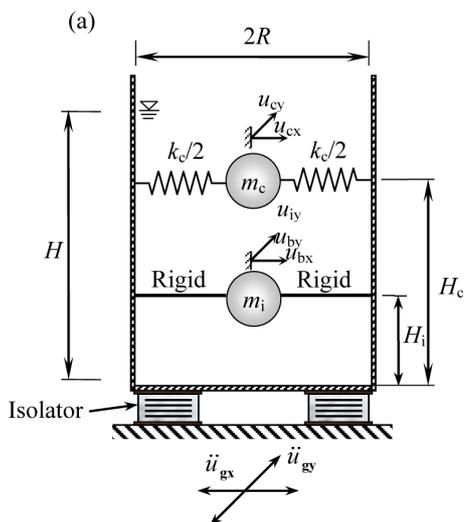
Herein, the base-isolated liquid storage tank is modeled using both, the two- and three mass models and the interaction of isolator hysteretic response is investigated under bi-directional earthquakes. Two different types of isolation systems, namely sliding system and elastomeric bearing, are considered for the present study. The major objectives of this study are: 1) to compare the seismic response using two different lumped mass models of base-isolated liquid storage tanks subjected to bi-directional earthquakes; and 2) to investigate the effect of interaction between the two mutually perpendicular hysteretic displacement components of isolation system.

2. MODELING OF BASE-ISOLATED LIQUID STORAGE TANKS

The ground supported cylindrical base-isolated liquid storage tank is modeled using two different lumped mass mechanical analogs: 1) two-mass model (Model 1) proposed by Housner [4] and 2) three-mass model (Model 2) proposed by Haroun and Housner [14]. **Figure 1** shows the two different models of the base-isolated liquid storage tanks. A brief detail of the models are provided here.

2.1. Two-Mass Model (Model 1)

This model divides the liquid column into two layers.



The upper layer, called convective mass, is considered to vibrate relative to the tank wall and resulting in the sloshing phenomenon, whereas the bottom layer, called impulsive mass, vibrates with the tank as rigid body and experience same earthquake acceleration as the base. The impulsive mass predominately contributes to the base shear and overturning moment of the tank. In this model, the convective mass (m_c) of the liquid is considered to be connected to the solid tank wall with certain stiffness (k_c) at a height H_c , whereas the impulsive mass (m_i) is connected rigidly to the tank wall at a height H_i . In the present study, only tanks with circular plan geometry are considered; hence, hereafter all the discussion will be restricted to circular tank only.

Figure 1(a) shows the schematic diagram of the tank model with the parameters mentioned above where total height of the liquid inside the tank is denoted by H and radius for circular tank is denoted by R .

The stiffness of the spring attached to the convective mass (k_c) as per this model is given by

$$k_c = 1.84(m_c g/R) \tanh(1.84 H/R) \quad (1)$$

where, g is the gravitational acceleration. Detailed expressions for the other parameters of the tank model are given in [4].

2.2. Three-Mass Model (Model 2)

In this model, Haroun and Housner [14] proposed an additional rigid mass (m_r), acting at a height of H_r , that rigidly moves along with the tank wall. The impulsive mass (m_i), acting at a height of H_i , is assumed in contact with the tank wall through a spring with stiffness k_i . Similarly, the convective or sloshing mass (m_c), acting at a height of H_c , is assumed in contact with the tank wall through a spring with stiffness k_c . They also considered a

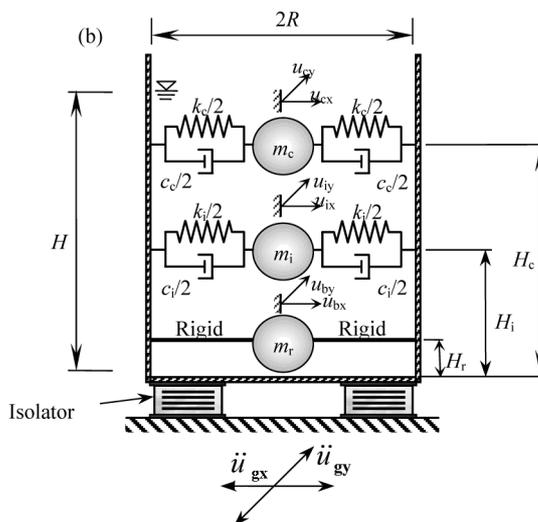


Figure 1. Schematic diagrams of the base-isolated liquid storage tanks: (a) Two-mass model (Model 1) and (b) Three-mass model (Model 2).

small amount of damping, for impulsive and sloshing mass.

Figure 1(b) shows the schematic diagram of Model 2 with all the parameters. The stiffness of the springs attached to the convective mass (k_c) is same as the Model 1; however, the stiffness of the spring attached to the impulsive mass (k_i) is given by

$$k_i = Em_i / \rho_s (P/H)^2 \quad (2)$$

where, E and ρ_s are the modulus of elasticity and density of the tank wall material, respectively; and P is a dimensionless parameter. The parameters of the tank are given in graphical form in [14]. The mathematical expressions of the parameters can be obtained from [11].

3. MODELING OF ISOLATION SYSTEM

For the present study, a non-linear model [15] is used to characterize the hysteretic force-deformation behavior of the isolation system, as shown in **Figure 2**. The behavior of the isolator is considered identical in both x - and y -directions. The restoring forces developed in these isolation systems for bi-directional excitation are given by

$$\begin{Bmatrix} F_{bx} \\ F_{by} \end{Bmatrix} = \alpha \begin{bmatrix} k_e & 0 \\ 0 & k_e \end{bmatrix} \begin{Bmatrix} x_b \\ y_b \end{Bmatrix} + (1-\alpha) F_y \begin{Bmatrix} Z_x \\ Z_y \end{Bmatrix} \quad (3)$$

where, F_y denotes yield strengths of the bearing in both x - and y -directions; α represents the ratio of post to pre-yield stiffness; k_e denotes pre-yield stiffness of the bearing in both x - and y -directions. Here, Z_x and Z_y denote non-dimensional hysteretic displacement components satisfying the following non-linear first order differential equation [16].

$$q \begin{Bmatrix} \ddot{Z}_x \\ \ddot{Z}_y \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{y}_b \end{Bmatrix} \quad (4)$$

where, $C_{11} = A - \beta \operatorname{sgn}(\dot{x}_b) |Z_x| Z_x^{n-1} - \tau Z_x^n$,
 $C_{12} = -\beta \operatorname{sgn}(\dot{y}_b) |Z_y| Z_x^{n-1} - \tau Z_x Z_y$,
 $C_{21} = -\beta \operatorname{sgn}(\dot{x}_b) |Z_x| Z_y^{n-1} - \tau Z_x Z_y$,
 and $C_{22} = A - \beta \operatorname{sgn}(\dot{y}_b) |Z_y| Z_y^{n-1} - \tau Z_y^n$.

In **Eq.4**, q denotes isolator yield displacement in both x - and y -directions; A , β and τ are dimensionless parameters; and parameter n is an integer constant, which controls smoothness of the transition from elastic to plastic response. These dimensionless parameters A , β , τ and n can be chosen in such a way that the model represents either a sliding system or an elastomeric system.

4. EQUATIONS OF MOTION

The governing equations of motion of the base-isolated liquid storage tank under bi-directional earthquake excitation are written in the matrix form as

$$[\bar{M}]\{\ddot{X}\} + [\bar{C}]\{\dot{X}\} + [\bar{K}]\{X\} + \{F\} = -[\bar{M}][r]\{\ddot{u}_g\} \quad (5)$$

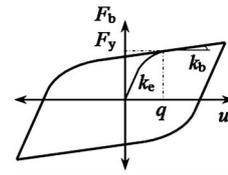


Figure 2. Non-linear Force-deformation behavior of the isolation system.

where, $\{X\}$ is the relative displacement vector; $\{F\}$ is the hysteretic restoring force vector; $[\bar{M}]$, $[\bar{C}]$ and $[\bar{K}]$ are the mass, damping and stiffness matrices of the system, respectively; $\{\ddot{u}_g\} = \{\ddot{u}_{gx} \ \ddot{u}_{gy}\}^T$ is the earthquake ground acceleration vector and $[r]$ is the influence coefficient matrix. The order of the vectors and matrices depend on the model of the liquid storage tank.

For Model 1, the mass matrix, $[\bar{M}]$, damping matrix, $[\bar{C}]$ and stiffness matrix, $[\bar{K}]$ can be written as

$$[\bar{M}] = \begin{bmatrix} m_c & m_c & 0 & 0 \\ m_c & M & 0 & 0 \\ 0 & 0 & m_c & m_c \\ 0 & 0 & m_c & M \end{bmatrix} \quad (6)$$

$$[\bar{C}] = \operatorname{diag}[c_c \ c_b \ c_c \ c_b] \quad (7)$$

$$[\bar{K}] = \operatorname{diag}[k_c \ k_b \ k_c \ k_b] \quad (8)$$

where, $M = m_c + m_i$. The displacement and hysteretic restoring vectors are given as

$$\{X\} = \{x_c \ x_b \ y_c \ y_b\}^T \quad (9)$$

$$\{F\} = \{0 \ (1-\alpha)F_y Z_x \ 0 \ (1-\alpha)F_y Z_y\}^T \quad (10)$$

where, $x_c = (u_{cx} - u_{bx})$ and $y_c = (u_{cy} - u_{by})$ are the displacements of the convective mass relative to the bearing displacement in x - and y -directions, respectively; $x_b = (u_{bx} - u_{gx})$ and $y_b = (u_{by} - u_{gy})$ are bearing displacements relative to the ground in x - and y -directions, respectively. The influence coefficient matrix takes the following form

$$[r] = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \quad (11)$$

For Model 2, the mass, $[\bar{M}]$, damping, $[\bar{C}]$ and stiffness, $[\bar{K}]$ matrices are given as

$$[\bar{M}] = \begin{bmatrix} m_c & 0 & m_c & 0 & 0 & 0 \\ 0 & m_i & m_i & 0 & 0 & 0 \\ m_c & m_i & M & 0 & 0 & 0 \\ 0 & 0 & 0 & m_c & 0 & m_c \\ 0 & 0 & 0 & 0 & m_i & m_i \\ 0 & 0 & 0 & m_c & m_i & M \end{bmatrix} \quad (12)$$

$$[\bar{C}] = \text{diag}[c_c \quad c_i \quad c_b \quad c_c \quad c_i \quad c_b] \quad (13)$$

$$[\bar{K}] = \text{diag}[k_c \quad k_i \quad k_b \quad k_c \quad k_i \quad k_b] \quad (14)$$

where, $M = m_c + m_i + m_b$. The displacement and hysteretic restoring vectors are given as

$$\{X\} = \{x_c \quad x_i \quad x_b \quad y_c \quad y_i \quad y_b\}^T \quad (15)$$

$$\{F\} = \{0 \quad 0 \quad (1-\alpha)F_y Z_x \quad 0 \quad 0 \quad (1-\alpha)F_y Z_y\}^T \quad (16)$$

where, $x_c = (u_{cx} - u_{bx})$ and $y_c = (u_{cy} - u_{by})$ are the displacements of the convective mass relative to the bearing displacement 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 the bearing displacements in x - and y -directions, respectively; $x_b = (u_{bx} - u_{gx})$ and $y_b = (u_{by} - u_{gy})$ are bearing displacements relative to the ground in x - and y -directions, respectively. The influence coefficient matrix takes the following form

$$[r] = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T \quad (17)$$

Numerical solution of **Eq.5** is obtain using Newmark's step-by-step integration technique, adopting linear variation of acceleration between two time steps, to determine the seismic response of the base-isolated liquid storage tank. Once the displacement and acceleration quantities are known, for Model 2, the base shears (V_{bx} and V_{by}) and overturning moments (M_{bx} and M_{by}) in either direction are

$$V_{bx} = m_c u_{cx} + m_i u_{ix} + m_r u_{bx} \quad (18)$$

$$V_{by} = m_c u_{cy} + m_i u_{iy} + m_r u_{by} \quad (19)$$

$$M_{bx} = m_c u_{cx} H_i + m_i u_{ix} H_i + m_r u_{bx} H_r \quad (20)$$

$$M_{by} = m_c u_{cy} H_i + m_i u_{iy} H_i + m_r u_{by} H_r \quad (21)$$

For Model 1, appropriate masses, accelerations and heights are to be taken for the calculation of the base shear and overturning moment.

5. NUMERICAL STUDIES

Ground supported cylindrical steel storage tanks are considered for the present study. Two different tank configurations are taken namely broad and slender. In **Table 1**, the geometrical properties of the cylindrical steel tanks are summarized. The thickness of the tank wall, used for Model 2, is denoted by t . The slenderness ratio (S) is determined by H/R . The liquid inside the tank is considered as water (mass density = 1000 kg/m³). For Model 2, the damping of the convective (ζ_c) and impulsive (ζ_i) masses are assumed as 0.5% and 2%, respectively. In the present study, two different types of the isolators are

studied, such as sliding system and elastomeric bearing. To model isolator force-deformation behavior, the dimensionless parameters of the Wen's model are chosen appropriately as given in **Table 2**. Total eight earthquake time histories, comprising of near-fault and far-fault ground motions, are considered. The details of the earthquake acceleration inputs are given in **Table 3**. The sliding system is characterized by the isolation time period (T_b) and friction coefficient (μ). Whereas, the elastomeric bearing is commonly characterized by its isolation time period (T_b) and damping (ζ_b), yield displacement (q) and the normalized yield strength (F_y/W), where, $W = Mg$ is the total weight of the structure. For the present study, T_b and μ for the sliding system is assumed as 2 sec and 0.05, respectively. The elastomeric bearing properties are assumed as, $T_b = 2$ sec, $\zeta_b = 0.1$ and $F_y/W = 0.05$.

The isolator force-deformation for the sliding system and elastomeric bearing are plotted in **Figure 3** for El-Centro earthquake. Model 1 represents the two mass mechanical analog, whereas Model 2 represents three mass mechanical analog. The isolator restoring forces (F_{bx} and F_{by}) are presented in normalized form in terms of the total weight of the structure (W). It is observed that the Wen's model can represent the force-deformation behavior of two different types of isolators, when the parameters are chosen appropriately.

5.1 Comparison of Seismic Response Obtained from Two Models

The peak seismic response quantities of base-isolated liquid storage tanks using the two models are compared herein. The important seismic response quantities considered are the base shears (V_{bx} and V_{by}), base displacements (x_b and y_b), sloshing displacements (x_c and y_c) and overturning moments (M_{bx} and M_{by}). For the sliding system, the isolation time period (T_b) is taken as 2 sec and the friction coefficient (μ) is taken as 0.05. The isolation time period (T_b), the isolation damping (ζ_b) and the normalized yield strength (F_y/W) of the elastomeric bearing are taken as 2 sec, 0.1 and 0.05, respectively. Two types of tank configurations, such as broad ($S = 0.6$) and

Table 1. Properties of the cylindrical tanks.

Type of tank	$S = H/R$	H (m)	t/R
Broad tank	0.6	14.6	0.004
Slender tank	1.85	11.3	0.004

Table 2. Parameters of the Wen's model.

Isolator	A	β	τ	n	q (cm)
Sliding system	1	0.9	0.1	2	0.025
Elastomeric bearing	1	0.5	0.5	2	2.5

Table 3. Details of the earthquake acceleration time histories.

Sl. no.	Event; record	Notation	Component	Direction	PGA ^a (g)
1	Imperial Valley, 1940; El-Centro	El-Centro	Normal (N)	x	0.26
			Parallel (P)	y	0.31
2	Imperial Valley, 1979; Array#5	Imperial #5	Normal (N)	x	0.36
			Parallel (P)	y	0.54
3	Imperial Valley, 1979; Array#7	Imperial #7	Normal (N)	x	0.45
			Parallel (P)	y	0.33
4	Loma Prieta, 1989; LGPC	Loma Prieta	Normal (N)	x	0.61
			Parallel (P)	y	0.56
5	Northridge, 1992; Rinaldi	Rinaldi	Normal (N)	x	0.87
			Parallel (P)	y	0.38
6	Northridge, 1992; Sylmar	Sylmar	Normal (N)	x	0.72
			Parallel (P)	y	0.58
7	Landers, 1992; Lucerne Valley	Lucerne	Normal (N)	x	0.71
			Parallel (P)	y	0.64
8	Kobe, 1995; JMA	Kobe	Normal (N)	x	0.60
			Parallel (P)	y	0.82

^aPGA = Peak ground acceleration.

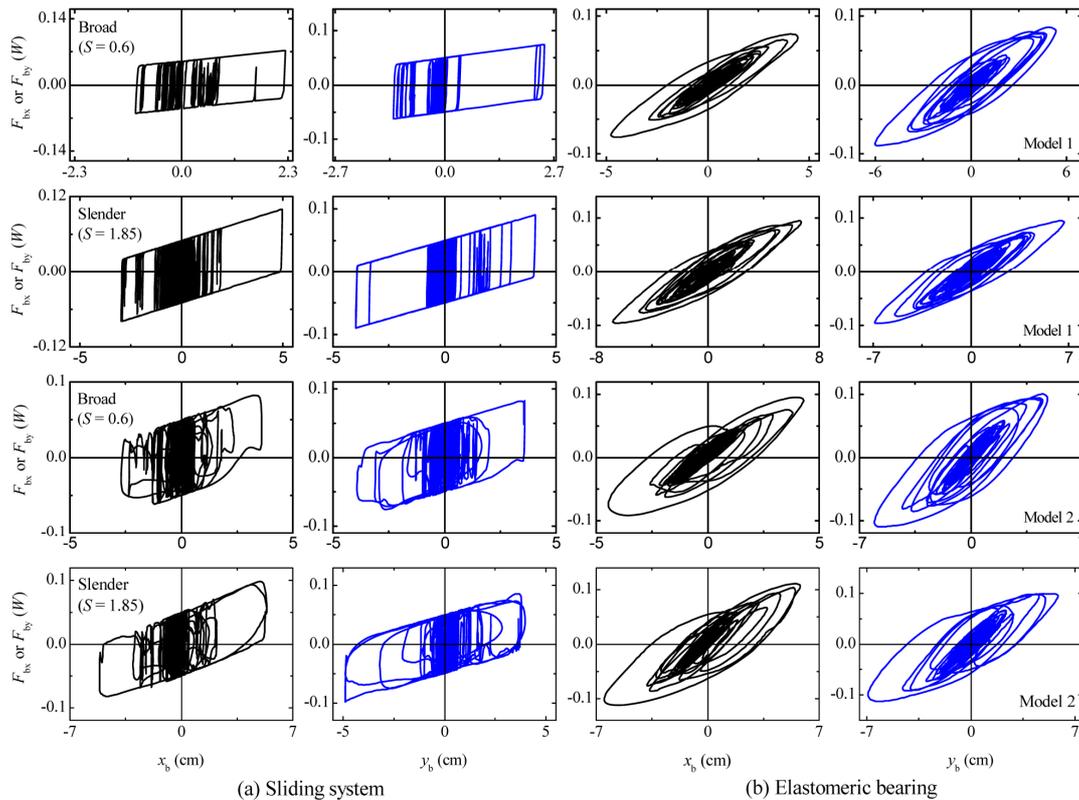


Figure 3. Isolator force-deformation behavior under El-Centro earthquake (for sliding system: $T_b = 2$ sec and $\mu = 0.05$; for elastomeric bearing: $T_b = 2$ sec, $\zeta_b = 0.1$, $q = 2.5$ cm, $F_y/W = 0.05$).

slender ($S = 1.85$), are studied. **Figures 4 and 5** show the response time histories under El-Centro earthquake for

the broad and slender tank configurations in x - and y -directions, respectively. The base shear and the overturn-

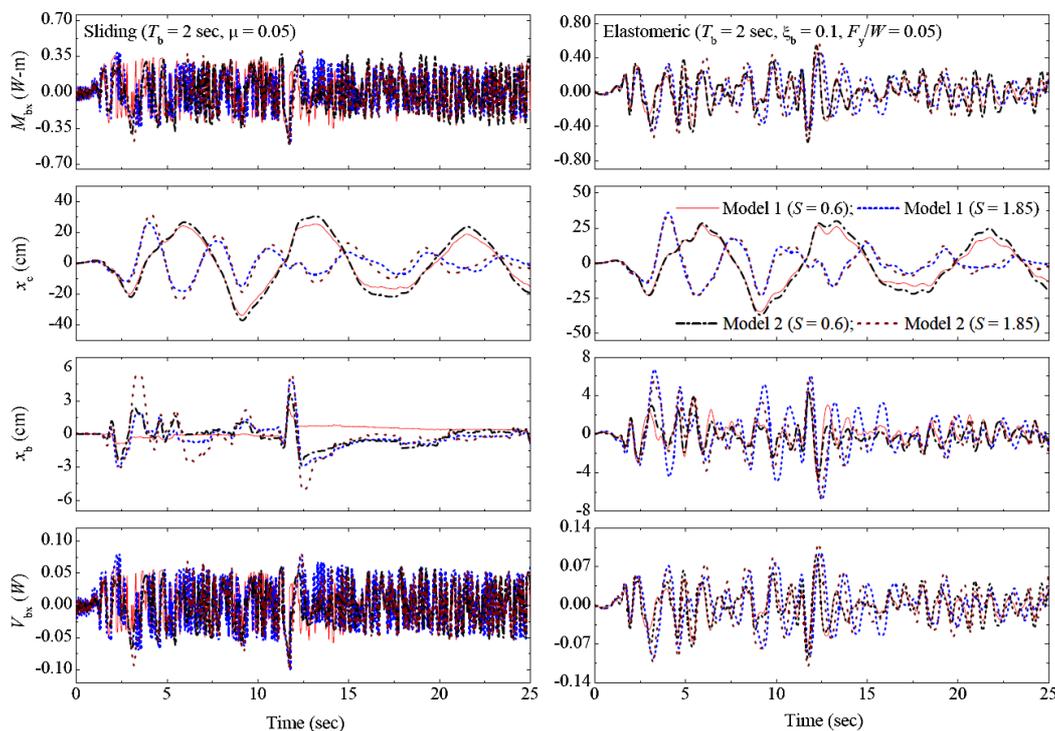


Figure 4. Time history of the response quantities along x -direction under bi-directional El-Centro earthquake.

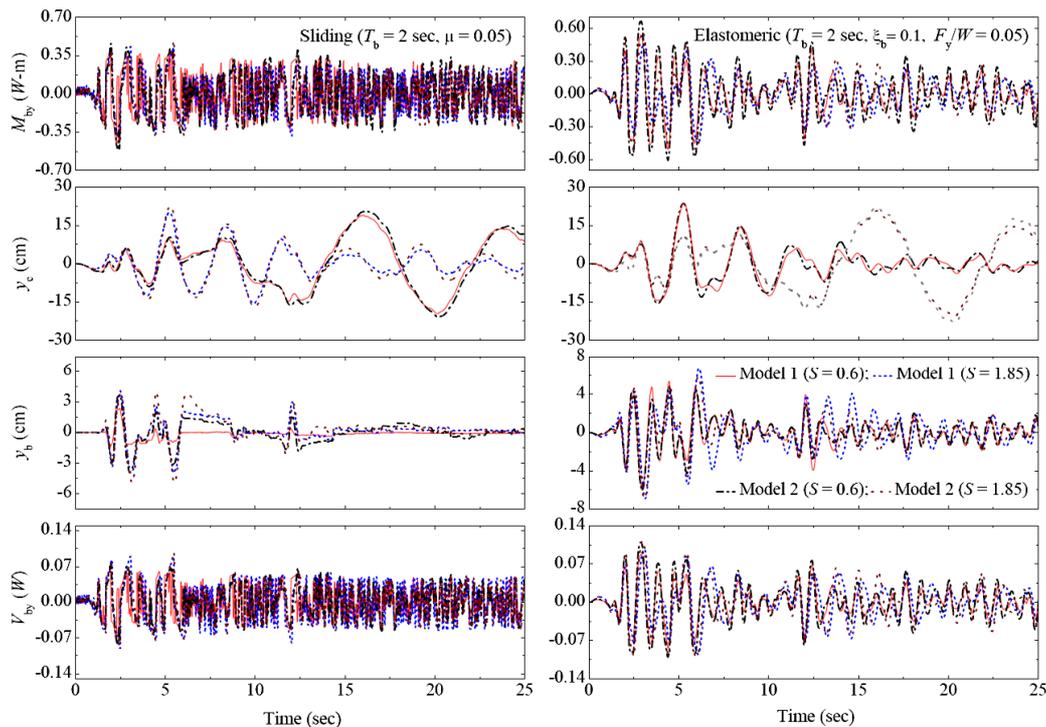


Figure 5. Time history of the response quantities along y -direction under bi-directional El-Centro earthquake.

ing moments are presented as normalized with respect to total weight of the structure (W).

It can be observed that there are considerable differences in the seismic response obtained by the two dif-

ferent modeling approaches for the liquid storage tanks. However, the sloshing displacement is not much affected by the modeling approaches. This phenomenon is also evident from Eq.1. The sloshing frequency is not influ-

Table 4. Peak seismic response quantities of base-isolated liquid storage tanks (for sliding system: $T_b = 2$ sec and $\mu = 0.05$; for elastomeric bearing: $T_b = 2$ sec, $\xi_b = 0.1$, $q = 2.5$ cm, $F_y/W = 0.05$).

Event	Isolator	Model	Broad ($S = 0.6$)						Slender ($S = 1.85$)									
			F_{bx} (W)	x_b (cm)	x_c (cm)	M_{bx} (W-m)	F_{bx} (W)	x_b (cm)	x_c (cm)	M_{bx} (W-m)	F_{bx} (W)	x_b (cm)	x_c (cm)	M_{bx} (W-m)				
El-Centro	Sliding	Model 1	0.074	2.5	33.8	0.032	0.083	3.3	21.5	0.010	0.095	5.0	29.8	0.028	0.090	4.7	20.8	0.001
		Model 2	0.083	3.6	37.0	0.034	0.083	3.9	26.9	0.012	0.098	5.4	31.9	0.046	0.099	4.9	22.6	0.021
	Elastomeric	Model 1	0.102	4.8	34.4	0.001	0.101	4.7	23.4	0.007	0.111	6.3	31.4	0.018	0.111	6.7	22.6	0.000
		Model 2	0.095	4.5	36.8	0.010	0.110	6.1	27.9	0.016	0.112	6.5	33.5	0.020	0.113	6.9	23.7	0.045
Imperial #5	Sliding	Model 1	0.104	8.3	116.5	0.004	0.099	6.3	128.9	0.014	0.270	22.4	161.3	0.061	0.129	9.8	58.2	0.005
		Model 2	0.144	12.6	123.2	0.018	0.114	7.4	148.8	0.135	0.265	23.4	177.1	0.046	0.135	10.4	64.2	0.057
	Elastomeric	Model 1	0.129	8.1	118.6	0.001	0.108	6.7	129.7	0.093	0.230	18.8	154.3	0.034	0.109	7.2	57.4	0.095
		Model 2	0.156	11.3	124.0	0.022	0.116	8.0	149.4	0.203	0.238	19.6	173.1	0.059	0.116	7.6	62.7	0.173
Imperial #7	Sliding	Model 1	0.177	13.3	86.3	0.127	0.104	8.5	75.8	0.090	0.258	22.4	164.2	0.087	0.118	11.2	48.6	0.042
		Model 2	0.207	16.7	104.9	0.194	0.111	9.8	90.6	0.172	0.265	24.9	182.9	0.195	0.129	12.3	57.5	0.082
	Elastomeric	Model 1	0.198	13.9	85.5	0.080	0.120	7.1	75.7	0.066	0.269	21.4	160.7	0.176	0.131	9.0	50.9	0.094
		Model 2	0.226	16.9	105.4	0.130	0.133	8.2	88.8	0.132	0.275	22.1	182.3	0.337	0.127	10.1	66.0	0.131
Loma Prieta	Sliding	Model 1	0.246	21.7	58.1	0.014	0.138	8.9	24.3	0.011	0.408	38.4	189.5	0.166	0.181	14.8	48.1	0.042
		Model 2	0.313	28.9	61.7	0.024	0.181	13.6	25.6	0.000	0.424	39.7	205.2	0.338	0.167	14.2	51.6	0.067
	Elastomeric	Model 1	0.198	14.0	59.0	0.048	0.128	7.0	23.3	0.010	0.287	23.6	162.7	0.135	0.153	10.6	41.0	0.014
		Model 2	0.227	17.9	61.2	0.070	0.146	9.4	24.0	0.025	0.323	26.3	183.7	0.257	0.149	10.6	44.0	0.010
Rinaldi	Sliding	Model 1	0.515	47.6	77.5	0.075	0.178	16.6	33.3	0.237	0.564	52.5	103.3	0.120	0.243	20.3	72.6	0.095
		Model 2	0.561	51.9	79.9	0.271	0.190	16.1	33.1	0.062	0.578	53.7	110.4	0.067	0.254	21.5	81.2	0.051
	Elastomeric	Model 1	0.432	35.6	70.0	0.194	0.099	7.9	26.7	0.040	0.498	42.9	79.1	0.094	0.191	14.0	68.5	0.125
		Model 2	0.482	40.6	71.8	0.377	0.151	10.8	28.7	0.061	0.511	44.3	86.0	0.127	0.194	15.2	75.8	0.184

Continued

Sylmar	Sliding	Model 1	0.299	25.0	69.4	0.030	0.151	12.2	20.1	0.038	0.473	43.0	133.4	0.004	0.335	29.4	35.6	0.010
		Model 2	0.383	33.9	75.7	0.001	0.212	19.6	26.9	0.033	0.495	45.4	144.4	0.146	0.324	30.0	35.9	0.047
	Elastomeric	Model 1	0.249	18.8	64.5	0.011	0.178	12.4	20.4	0.033	0.394	33.0	109.5	0.006	0.226	17.2	21.2	0.008
		Model 2	0.312	25.5	69.3	0.006	0.184	13.5	20.3	0.040	0.417	35.3	118.9	0.057	0.240	18.4	21.6	0.023
Lucerne	Sliding	Model 1	0.104	7.9	183.4	0.113	0.109	5.9	81.9	0.126	0.298	24.7	151.8	0.066	0.151	11.4	23.7	0.066
		Model 2	0.146	12.8	196.5	0.261	0.131	8.1	86.2	0.050	0.310	26.0	175.5	0.269	0.154	11.8	25.8	0.001
	Elastomeric	Model 1	0.126	7.7	183.3	0.110	0.107	5.6	83.0	0.059	0.254	21.0	152.0	0.137	0.150	10.6	24.7	0.000
		Model 2	0.150	10.2	196.3	0.186	0.124	7.3	86.7	0.087	0.269	22.5	176.1	0.391	0.154	11.2	27.9	0.034
Kobe	Sliding	Model 1	0.313	26.9	47.6	0.024	0.203	19.3	34.9	0.003	0.328	28.9	62.5	0.036	0.192	15.6	61.8	0.023
		Model 2	0.378	33.0	43.6	0.003	0.200	16.4	29.3	0.020	0.337	29.8	64.4	0.127	0.193	15.8	72.3	0.060
	Elastomeric	Model 1	0.269	19.8	33.1	0.002	0.206	15.9	25.3	0.008	0.248	18.1	52.8	0.028	0.195	14.0	50.5	0.033
		Model 2	0.260	19.1	34.4	0.022	0.195	14.3	24.6	0.021	0.245	19.6	55.9	0.103	0.196	14.1	59.4	0.085

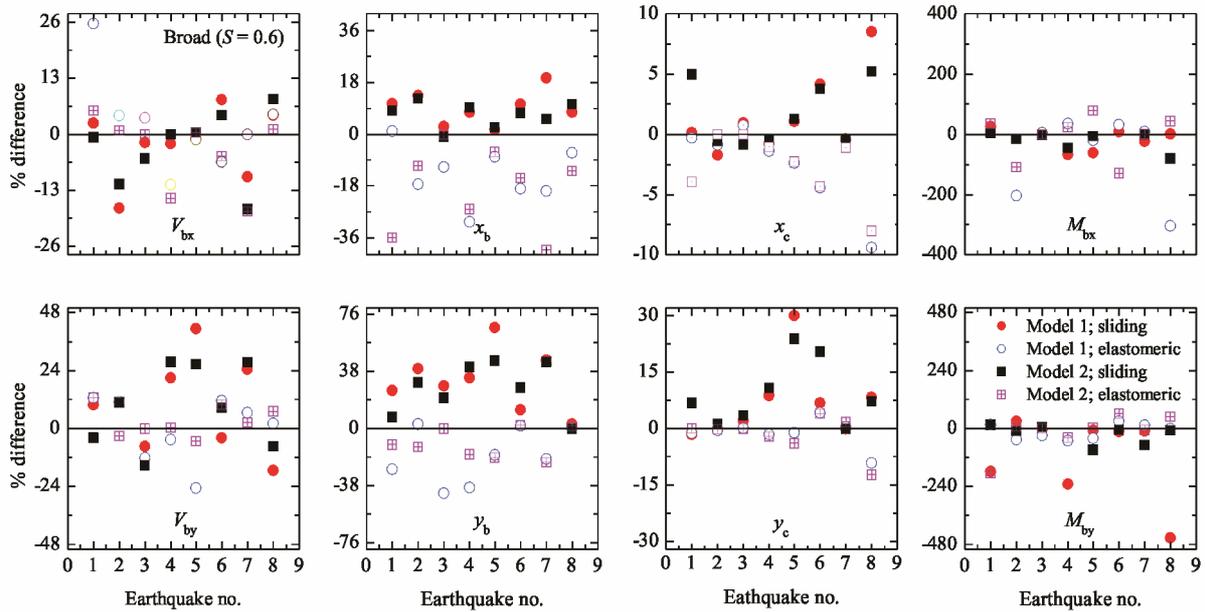


Figure 6. Effect of seismic response interaction on broad tank (for sliding system: $T_b = 2$ sec and $\mu = 0.05$; for elastomeric bearing: $T_b = 2$ sec, $\zeta_b = 0.1$, $q = 2.5$ cm, $F_y/W = 0.05$).

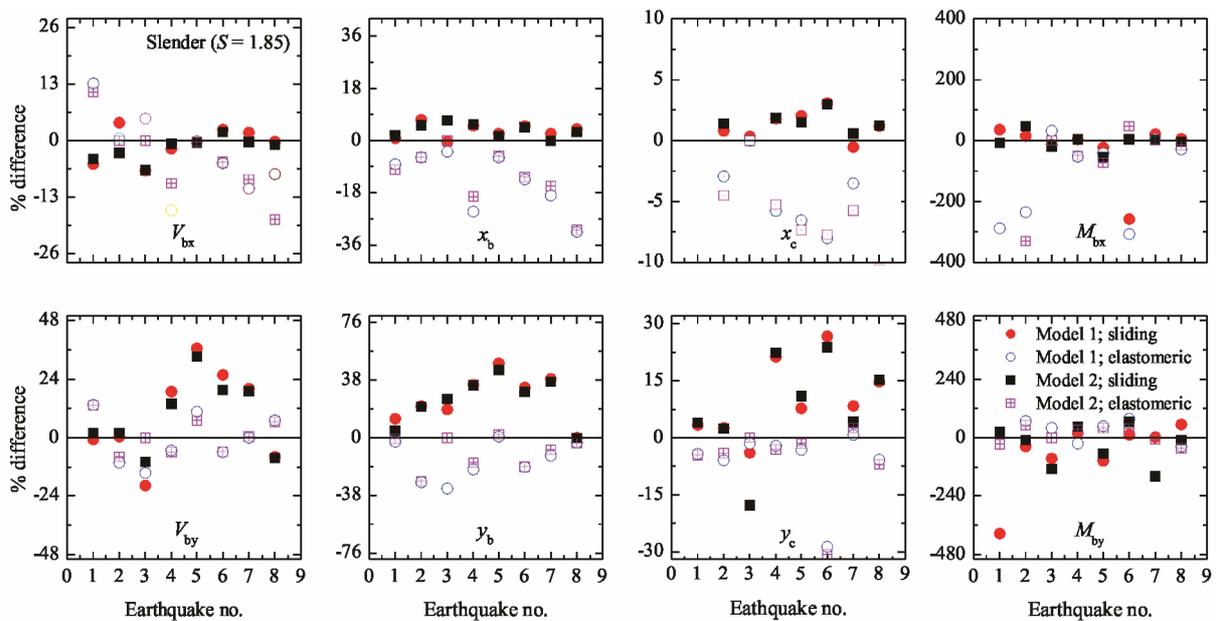


Figure 7. Effect of seismic response interaction on slender tank (for sliding system: $T_b = 2$ sec and $\mu = 0.05$; for elastomeric bearing: $T_b = 2$ sec, $\zeta_b = 0.1$, $q = 2.5$ cm, $F_y/W = 0.05$).

enced by the material properties of the tank wall, and they are the same for both the tank models. Hence, their seismic response time histories are also not affected by the modeling approaches. However, with the inclusion of an additional rigid mass the impulsive frequency changes in Model 2. As a result, the base shear, base displacement and overturning moment differ with the modeling approaches. It is further observed that the computed base shear and overturning moment of the liquid storage tank,

isolated by sliding system, contains significant high frequency response, which is also observed for building like structure [17].

The peak seismic response quantities of the broad and slender tanks are compared in **Table 4** for all the earthquakes given in **Table 3**. It can be observed that the Model 1 underestimate the peak seismic response of the base-isolated liquid storage tanks. However, peak sloshing displacements, computed using the two different

modeling approaches, are not affected for both the tank configurations. Furthermore, the difference in the seismic response, obtained through two different modeling approaches, is more for broad tanks as compared to slender tanks. It can also be observed that most of the seismic response quantities are increased when the tank is base-isolated using sliding system as compared to case when the tank is base-isolated using elastomeric bearing, except the base displacements (x_b and y_b).

5.2 Effect of Interaction on the Peak Seismic Response

The effect of interaction between two mutually perpendicular hysteretic displacement components of the isolator under bi-directional earthquake excitation is studied. For the sliding system, the isolation time period (T_b) is taken as 2 sec and the friction coefficient (μ) is taken as 0.05. The isolation time period (T_b), the isolation damping (ζ_b) and the normalized yield strength (F_y/W) of the elastomeric bearing are taken as 2 sec, 0.1 and 0.05, respectively. Two types of tank configurations, such as broad ($S = 0.6$) and slender ($S = 1.85$), are studied. **Figures 6** and **7** show the percentage difference of the peak seismic response quantities for broad and slender tank configurations, respectively. For example, % difference in the base displacement in x -direction (x_b) is calculated as

$$\% \text{ difference in } x_b = \frac{(x_b)_{\text{interaction}} - (x_b)_{\text{no-interaction}}}{(x_b)_{\text{interaction}}} \times 100 \quad (22)$$

where, $(x_b)_{\text{interaction}}$ and $(x_b)_{\text{no-interaction}}$ indicates the peak base displacement when interaction is considered and not considered, respectively. Here, zero percentage indicates that there is no effect of interaction on the seismic response. A negative percentage indicates that the peak seismic response is more when response interaction is not considered.

It is observed that both the models of the base-isolated liquid storage tanks are showing similar trend to predict the effect of response interaction of broad and slender tanks. It is also observed that the effect of interaction is most significant for base displacement. Sloshing displacement is less affected by the interaction. Base shear and overturning moment are also influenced by the consideration of the interaction. The effect of the interaction in bi-directional seismic response is observed to be marginally more in the broad tanks as compared to the slender tanks, and the seismic response along y -direction is more influenced by the interaction than along x -direction. It is further observed that the consideration of the interaction affect the seismic response differently in case

of sliding system and elastomeric bearing. The effect of interaction in case of the sliding system is more pronounced than in case of the elastomeric bearing. For sliding system, the base displacement increases when the interaction is considered. However, for elastomeric bearing interaction reduces the base displacement.

6. CONCLUSIONS

Seismic response of base-isolated liquid storage tanks is investigated under bi-directional earthquakes. The liquid storage tank is modeled using a) two mass and b) three mass mechanical analogs. Two different isolation systems, namely sliding system and elastomeric bearing, are considered. A comparison of the important response quantities, obtained through two different modeling approaches of the tank, is carried out. The effects of the interaction, between the two mutually perpendicular hysteretic displacement components of the isolator, on the response, are also studied. Following are the major conclusions drawn from the present study.

- 1) The two-mass model (Model 1) and three-mass model (Model 2) of the base-isolated liquid storage tanks estimate almost the same sloshing displacement. However, base shear, base displacement and overturning moment are underestimated by the two-mass model as compared to the three-mass model.
- 2) The base shear and overturning moment of the liquid storage tank, isolated by sliding system, contains significant high frequency components.
- 3) The difference in the peak response, obtained through Model 1 and Model 2, is more for broad tanks.
- 4) Peak seismic response quantities, except base displacements, are increased when the tank is base-isolated using sliding system as compared to case when the tank is base-isolated using elastomeric bearing.
- 5) Consideration of interaction between two mutually perpendicular hysteretic displacement components of the isolator significantly affects the peak response of the base-isolated liquid storage tanks.
- 6) Effect of the interaction under bi-directional earthquake is predicted similarly by the Model 1 and Model 2.

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