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Response of base-isolated liquid storage tanks to near-fault motions

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Abstract. Seismic response of the liquid storage tanks isolated by the elastomeric bearings and sliding systems is investigated under near-fault earthquake motions. The fault normal and parallel components of near-fault motion are applied in two horizontal directions of the tank. The continuous liquid mass of the tank is modeled as lumped masses known as sloshing mass, impulsive mass and rigid mass. The corresponding stiffness associated with these lumped masses has been worked out depending upon the properties of the tank wall and liquid mass. It is observed that the resultant response of the isolated tank is mainly governed by fault normal component with minor contribution from the fault parallel component. Further, a parametric study is also carried out to study the effects of important system parameters on the effectiveness of seismic isolation for liquid storage tanks. The various important parameters considered are: aspect ratio of tank, the period of isolation and the damping of isolation bearings. There exists an optimum value of isolation damping for which the base shear in the tank attains the minimum value under near-fault motion. The increase of damping beyond the optimum value will reduce the bearing and sloshing displacements but increases the base shear. A comparative performance of five isolation systems for liquid storage tanks is also studied under normal component of near-fault motion and found that the EDF type isolation system may be a better choice for design of isolated tank in near-fault locations. Finally, it is also observed that the satisfactory response can be obtained by analysing the base-isolated tanks under simple cycloidal pulse instead of complete acceleration history.

Keywords: base isolation; liquid storage tank; elastomeric bearings; sliding systems; near-fault motion; system parameters; cycloidal pulse.

1. Introduction

Liquid storage tanks are strategically very important structure, since it has vital use in industries, nuclear power plants and connected to the public life. There had been a number of reports on damage to liquid storage tanks in the past earthquake (Steinbrugge and Rodrigo 1963, Niwa and Clough 1982). The earthquake damage has been due to number of causes with the most common being buckling of tank wall due to excessive development of compressive stresses in the wall, failure of piping system and uplift of the anchorage system. The integrity of any structure can be protected from the attack of severe earthquakes either through the concept of resistance or isolation.

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In designing a structure by resistance, it is assumed that the earthquake forces can be transmitted directly 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 structure.

The base isolation techniques had been developed and successfully implemented to buildings in the past (Kelly 1986, Jangid and Datta 1995). However, there had been very few studies in the past to investigate the effectiveness of base isolation for aseismic design of liquid storage tanks. Chalhoub and Kelly (1990) conducted shake table test on base-isolated cylindrical water tanks and compared the response with corresponding response of non-isolated tanks. A significant reduction in hydrodynamic forces with slight increase of free-water surface was observed due to isolation. Liang and Tang (1994) investigated the seismic response of flexible liquid storage tanks isolated by lead-rubber bearings. The investigation revealed that isolation was effective in reducing the seismic response of the tanks. Kim and Lee (1995) experimentally investigated the seismic performance of liquid storage tanks isolated by laminated rubber bearings under uni-directional excitation and shown that the isolation was effective in reducing the dynamic response. Malhotra (1997) studied the seismic response of cylindrical liquid storage tanks, under uni-directional ground motion, in which wall of the tank was isolated from the base plate by horizontal flexible rubber bearings. The numerical results indicated that the isolation was quite effective in reducing the axial stresses in the cylindrical shell. The numerical results also indicated that the sloshing displacement of base-isolated liquid storage tank was increased but decrease in axial stresses in cylindrical shell was significant to avoid the buckling of the shell. Wang *et al.* (2001) observed that seismic performance of liquid storage tanks isolated by sliding system under uni-directional excitation and found that isolation system was effective to reduce the response. Recently, Shrimali and Jangid (2004) presented the earthquake analysis of base-isolated liquid storage tanks using linear theory of base isolation.

Several seismologists have suggested that base-isolated buildings are vulnerable to large pulse-like ground motions generated at near-fault locations (Heaton *et al.* 1995, Hall *et al.* 1995). The base-isolated buildings might perform poorly because of large isolator displacements due to long period pulses associated in the near-fault motion. These concerns have influenced the seismic isolation design requirements in recent codes (UBC 1997). In the earlier code there were no near-fault factors but in the recent code, near-fault factors have been introduced that make it uneconomic to use isolation in such sites. There have been several studies for understanding the dynamic behaviour of base-isolated buildings under near-fault motion (Makris 1997, Makris and Chang 2000, Jangid and Kelly 2001, Rao and Jangid 2001). It has been observed that the seismic response of structure under near-fault motion is quite different as compared to the corresponding response with far-fault motion. Since the above studies of base-isolated structure under near-fault motions applied to buildings and it will be interesting to study the behaviour of base-isolated tanks under near-fault motion.

In this paper, the seismic response of ground-supported liquid storage tanks isolated by elastomeric bearings and sliding systems is investigated under near-fault earthquake motions. The specific objectives of the study are to (i) study the effectiveness base isolation for liquid storage tanks under near-fault motions, (ii) study the response of base-isolated tanks under normal and parallel component of near-fault motions, (iii) study the influence of isolation system parameters on the effectiveness base isolation for liquid storage tanks, (iv) study the comparative performance of different isolation systems for liquid storage tanks under near-fault motion and (v) to compare the response of isolated liquid storage tanks under near-fault earthquake motion and cycloidal pulse motion.

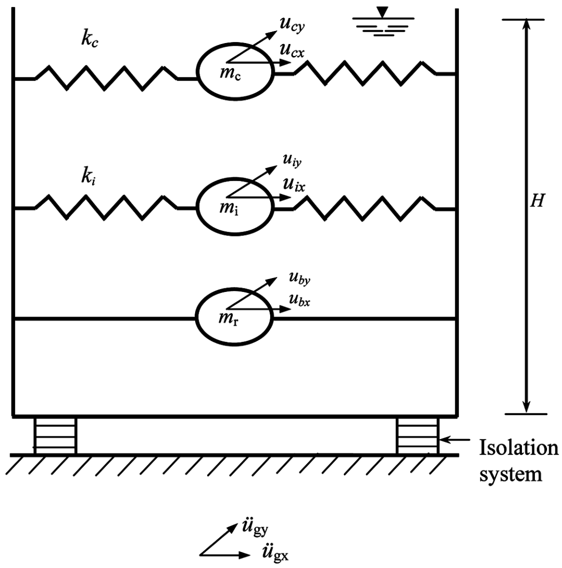


Fig. 1 Structural model of base-isolated liquid storage tank

2. Sturctural model of liquid storage tank

The structural model considered for the base-isolated cylindrical liquid storage tank is shown in Fig. 1 in which the isolation systems are installed between the base and foundation of the tank. 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 or convective 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). There are various modes in which sloshing and impulsive masses vibrates but the response can be predicted by considering first sloshing mode and first impulsive mode as observed experimentally by Kim and Lee (1995) and numerically by Malhotra (1997). Therefore, the continuous liquid is modelled as lumped masses with flexible tank proposed by Haroun (1983). The sloshing, impulsive and rigid lumped masses are denoted by m_c, m_i and m_r, respectively. The sloshing and impulsive masses are connected to the tank wall by corresponding equivalent spring having stiffness, k_c $(=m_c\omega_c^2)$ and k_i $(=m_i\omega_i^2)$, respectively. The parameters ω_c and ω_i denote the sloshing and impulsive frequencies of the liquid mass, respectively. The damping constant of the sloshing and impulsive masses are c_c and c_i, respectively. The system has six-degrees-of-freedom under near-fault earthquake ground motion, two-degrees-of-freedom of each lumped mass in two horizontal x and y-directions. These degrees-of-freedom are denoted by (u_{cx}, u_{cy}), (u_{ix}, u_{iy}) and (u_{bx}, u_{by}) which denote the absolute displacement of sloshing, impulsive and rigid masses in x and y-directions, respectively. The tank model is assumed to have non-deformable cylindrical shell.

The parameters of the tank considered are liquid height, H radius, R and average thickness of tank wall, t_h. The lumped masses in terms of the liquid mass, m are expressed as

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

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

$$m_c = Y_r m \tag{3}$$

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

where ρ_w is the mass density of liquid. The Y_c, Y_i and Y_r are the mass ratios which are function of the tank wall thickness and aspect ratio of the tank. For t_h/R = 0.004, the various mass ratios are expressed (Haroun 1983) as

$$Y_c = 1.01327 - 0.87578S + 0.35708S^2 - 0.06692S^3 + 0.00439S^4 \tag{5}$$

$$Y_i = -0.15467 + 1.21716S - 0.62839S^2 + 0.14434S^3 - 0.0125S^4 \tag{6}$$

$$Y_r = -0.01599 + 0.86356S - 0.30941S^2 + 0.04083S^3 \tag{7}$$

where $S = H/R$ is the aspect ratio (i.e., ratio of the liquid height to radius of the tank).

The fundamental frequency of impulsive mass, ω_i and of sloshing mass, ω_c are given by following expressions as (Haroun 1983)

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

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

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

$$P = 0.037085 + 0.084302S - 0.05088S^2 + 0.12523S^3 - 0.0012S^4 \tag{10}$$

The equivalent stiffness and damping constants of the sloshing and impulsive masses are expressed as,

$$k_c = m_c \omega_c^2 \tag{11}$$

$$k_i = m_i \omega_i^2 \tag{12}$$

$$c_c = 2\xi_c m_c \omega_c \tag{13}$$

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

where ξ_c and ξ_i are the damping ratios of the sloshing and impulsive masses, respectively.

2.1 Governing equations of motion

The equations of motion of isolated liquid storage tank in x-direction subjected to earthquake ground motion are expressed for different systems as,

$$m_c\ddot{x}_c + c_c\dot{x}_c + k_c x_c = -m_c(\ddot{x}_b + \ddot{x}_g) \tag{15}$$

$$m_i\ddot{x}_i + c_i\dot{x}_i + k_i x_i = -m_i(\ddot{x}_b + \ddot{x}_g) \tag{16}$$

$$(m_c + m_i + m_r)\ddot{x}_b + F_{bx} = -(m_c + m_i + m_r)\ddot{x}_g \tag{17}$$

where $x_c = u_{cx} - u_{bx}$ is the displacement of the sloshing mass relative to bearing displacement in x-direction, $x_i = u_{ix} - u_{bx}$ is the displacement of the impulsive mass relative to bearing displacement in x-direction; $x_b = u_{bx} - u_{gx}$ is the displacement of the bearings relative to ground in x-direction; F_{bx} is the restoring force of the isolation system in the x-direction; and $\ddot{x}_g$ is the earthquake acceleration acting in the x-direction.

The equations of motion for isolated tank in y-direction can be obtained by replacing x to y in Eqs. (15-17).

3. Isolation systems

3.1 Laminated rubber bearing

The laminated rubber bearings (LRB) base isolation system is the most common system. The basic components of the LRB are steel and rubber plates built in the alternate layers. The dominant features of the LRB system are the parallel action of linear spring and damping. Generally, the LRB system exhibits high-damping capacity, horizontal flexibility and high vertical stiffness. The LRB system is modelled with linear force-deformation behaviour and viscous damping (refer Fig. 2(a) for schematic model). The restoring forces, F_{bx} and F_{by} of the LRB system are expressed by

$$\begin{Bmatrix} F_{bx} \\ F_{by} \end{Bmatrix} = \begin{bmatrix} c_b & 0 \\ 0 & c_b \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{y}_b \end{Bmatrix} + \begin{bmatrix} k_b & 0 \\ 0 & k_b \end{bmatrix} \begin{Bmatrix} x_b \\ y_b \end{Bmatrix} \tag{18}$$

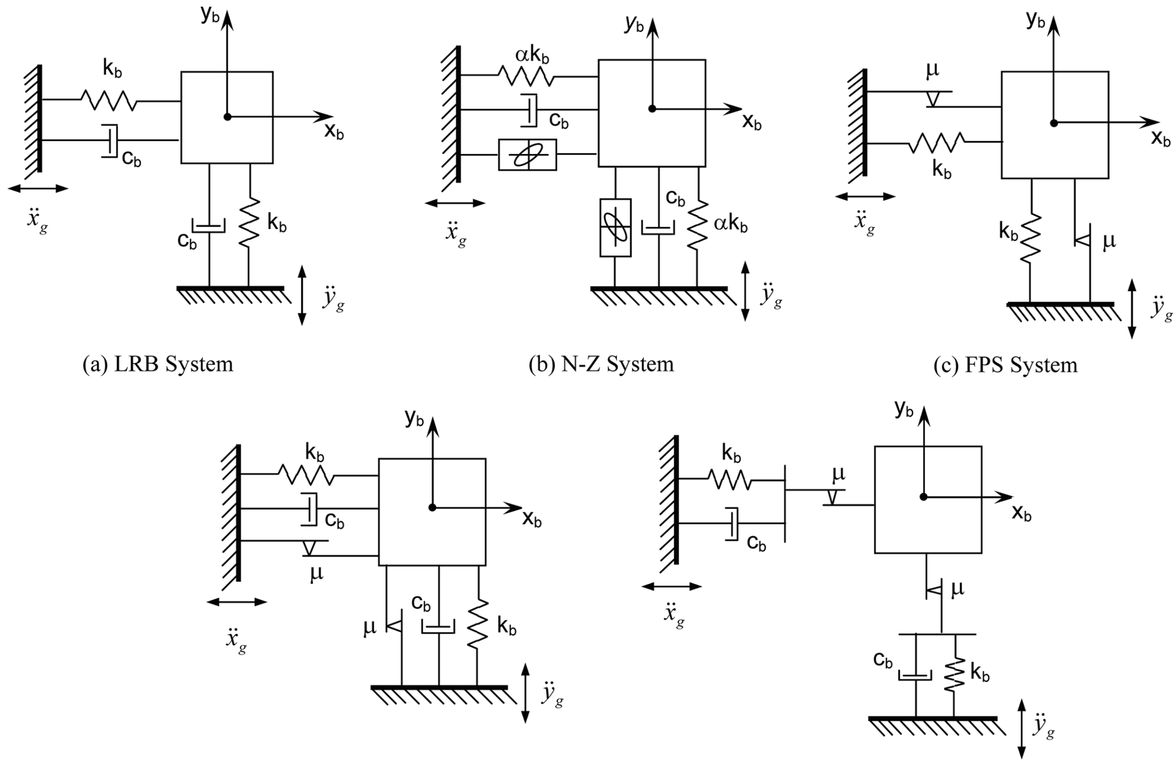
where k_b and c_b are the horizontal stiffness and viscous damping of the bearing, respectively.

The required stiffness and damping of the LRB system are designed such that to provide specific values of the two parameters namely the isolation period (T_b) and damping ratio (ξ_b) defined as

$$T_b = 2\pi\sqrt{\frac{M}{k_b}} \tag{19}$$

$$\xi_b = \frac{c_b}{2M\omega_b} \tag{20}$$

where $\omega_b = 2\pi/T_b$ is the isolation frequency; $M = m_c + m_i + m_r$ is the total effective mass of the isolated liquid storage tank.



(a) LRB System (b) N-Z System (c) FPS System

(d) R-FBI System (e) EDF System

Fig. 2 The schematic diagram of different isolation systems

3.2 Lead-rubber bearings

These bearings are similar to the LRB but a central lead core is used to provide an additional means of energy dissipation and initial rigidity against minor earthquakes and winds. These bearings are widely used in New Zealand and are generally referred as N-Z system. The energy absorbing capacity by the lead core reduces the lateral displacements of the isolator. The lead-rubber bearings also provide an additional hysteretic damping through the yielding of lead core. The hysteresis loop of N-Z system is generally modelled by bi-linear force-deformation behaviour with schematic behaviour shown in Fig. 2(b). The non-linear restoring forces of the N-Z system is modelled by coupled differential equations as proposed by Park *et al.* (1986) which is used in the past by Nagarajaiah *et al.* (1991) and Jangid and Datta (1994). The restoring forces of the N-Z system in two horizontal directions are given by

$$\begin{Bmatrix} F_{bx} \\ F_{by} \end{Bmatrix} = \begin{bmatrix} c_b & 0 \\ 0 & c_b \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{y}_b \end{Bmatrix} + \alpha \begin{bmatrix} k_b & 0 \\ 0 & k_b \end{bmatrix} \begin{Bmatrix} x_b \\ y_b \end{Bmatrix} + (1-\alpha) \begin{bmatrix} Q_y & 0 \\ 0 & Q_y \end{bmatrix} \begin{Bmatrix} Z_x \\ Z_y \end{Bmatrix} \tag{21}$$

where Z_x and Z_y are the hysteretic displacement components of restoring forces in x- and y-directions respectively; α is the post to pre-yield stiffness ratio (such that αk_b is the post yield stiffness of the bearing); k_b and c_b denote the initial stiffness and viscous damping, respectively; and Q_y is the yield force. The hysteretic displacement components Z_x and Z_y satisfy the following coupled non-linear first order differential equations i.e.,

$$q\begin{Bmatrix}\dot{Z}_x\\ \dot{Z}_y\end{Bmatrix} = [G]\begin{Bmatrix}\dot{x}_b\\ \dot{y}_b\end{Bmatrix} \tag{22}$$

and

$$[G] = \begin{bmatrix} A-\beta\mathrm{sgn}(\dot{x}_b)|Z_x|Z_x-\tau Z_x^2 & -\beta\mathrm{sgn}(\dot{y}_b)|Z_y|Z_x-\tau Z_xZ_y \\ -\beta\mathrm{sgn}(\dot{x}_b)|Z_x|Z_y-\tau Z_xZ_y & A-\beta\mathrm{sgn}(\dot{y}_b)|Z_y|Z_y-\tau Z_y^2 \end{bmatrix} \tag{23}$$

where β, τ and A are the parameters, which controls the shape and size of the hysteretic loop; q is the yield displacement and sgn denotes the sign function. The force-deformation behaviour of elastomeric bearing can be modelled by selecting properly the parameters α, β, τ and A.

The N-Z bearings are generally designed to specified values of three parameters namely: the isolation period, T_b, the damping ratio, ξ_b and the normalized yield strength, F_0. The parameters T_b and ξ_b are obtained from Eqs. (19) and (20), respectively based on the post-yield stiffness of the bearing. The parameter, F_0 is defined as

$$F_0 = \frac{Q_y}{W} \tag{24}$$

where $W = Mg$ is the total effective weight of the tank; and g is acceleration due to gravity.

The other parameters of the hysteresis loop of the N-Z system are held constant and values taken as, q = 2.5 cm, A = 1, and $\beta = \tau = 0.5$.

3.3 Friction pendulum system

The frictional pendulum system (FPS) uses geometry and gravity to achieve the desired seismic isolation (Zayes *et al.* 1990). The structure supported on FPS system responds to earthquake motions with small amplitude pendulum motion. The friction damping absorbs the earthquake's energy. The schematic model of the FPS system is shown in Fig. 2(c). The restoring forces of the FPS system are expressed by

$$\begin{Bmatrix}F_{bx}\\ F_{by}\end{Bmatrix} = \begin{Bmatrix}F_x\\ F_y\end{Bmatrix} + \begin{bmatrix}k_b & 0\\ 0 & k_b\end{bmatrix}\begin{Bmatrix}x_b\\ y_b\end{Bmatrix} \tag{25}$$

where F_x and F_y are the frictional forces in x and y-direction of the system, respectively; and k_b is the equivalent stiffness provided by the curvature of the FPS system.

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

$$F_s = \mu Mg \tag{26}$$

where μ is the friction coefficient of the sliding system.

The stiffness of the FPS system is evaluated for a specific value of the parameter isolation period, T_b expressed by Eq. (19). Thus, the FPS system requires the specifications of the parameters T_b and μ.

3.4 Resilient-friction base isolator

The resilient-friction base isolator (R-FBI) system was proposed by Mostaghel and Khodaverdian (1987). This base isolator consists of concentric layers of Teflon-coated plates that are in friction contact with each other and contains a central core of rubber. It combines the beneficial effect of friction damping with that of resiliency of rubber. The rubber core distributes the sliding displacement and velocity along the height of the R-FBI bearing. The system provides isolation through the parallel action of friction, damping and restoring force. The schematic model of the R-FBI system is shown in Fig. 2(d) and the force-deformation characteristic is expressed by

$$\begin{Bmatrix} F_{bx} \\ F_{by} \end{Bmatrix} = \begin{Bmatrix} F_x \\ F_y \end{Bmatrix} + \begin{bmatrix} k_b & 0 \\ 0 & k_b \end{bmatrix} \begin{Bmatrix} x_b \\ y_b \end{Bmatrix} + \begin{bmatrix} c_b & 0 \\ 0 & c_b \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{y}_b \end{Bmatrix} \tag{27}$$

where F_x and F_y are the frictional forces in x and y-direction of the system, respectively; and k_b and c_b are the stiffness and viscous damping of the central rubber core of R-FBI system, respectively.

The stiffness and damping of R-FBI system are evaluated to provide the desired value of parameters namely the isolation period, T_b and the damping ratio, ξ_b expressed by Eqs. (19) and (20), respectively. Thus, the R-FBI system requires the specification of the parameters T_b, ξ_b and μ.

3.5 EDF system

An important friction type base isolator (Gueraud *et al.* 1985) is a system developed under the auspices of "Electric de France" (EDF). This system is standardized for nuclear power plants in regions of high seismicity and is constructed by French company "Framatome". The EDF system consists of laminated (steel-reinforced) Neoprene pad topped by a lead-bronze plate which is in frictional contact with a steel plate anchored to the base raft of the structure. Thus, the EDF system is almost same as LRB system with top frictional plate. An attractive feature of the EDF isolator is that for lower amplitude ground excitations, the lateral flexibility of Neoprene pad provides base isolation. On the other hand, at high level of excitation, sliding will occur which provides additional protection. The schematic model of EDF system is shown in Fig. 2(e). The force-deformation characteristics of the EDF system requires the specification of the stiffness and damping of Neoprene pad to provide the desired value of isolation period (T_b) and damping ratio (ξ_b), respectively. The top plate of EDF system is designed for a desired value coefficient of friction, μ.

4. Incremental solution of equations of motion

The governing equations motion of the isolated liquid storage tank cannot be solved using the classical modal superposition technique due to (i) the damping in the isolation system and liquid storage tank is different in nature because of material characteristics and (ii) the force-deformation behaviour of the N-Z, FPS, R-FBI and EDF system is non-linear. As a result, the governing equations of motion are solved in the incremental form using Newmark's step-by-step method assuming linear variation of acceleration over small time interval, Δt.

The total base shear generated due to earthquake ground motion in x and y-directions, of the tank is expressed as

$$F_{sx} = m_c\ddot{u}_{cx} + m_i\ddot{u}_{ix} + m_r\ddot{u}_{bx} \quad (28)$$

$$F_{sy} = m_c\ddot{u}_{cy} + m_i\ddot{u}_{iy} + m_r\ddot{u}_{by} \quad (29)$$

Table 1 Near-fault earthquake motions recorded in California

Earthquake	Recording station	Peak acceleration (g)	
		Normal component	Parallel component
October 15, 1979 Imperial Valley	Array # 5	0.36	0.54
October 15, 1979 Imperial Valley	Array # 7	0.45	0.33
June 28, 1992 Landers	Lucerne valley	0.71	0.64
January 17, 1994 Northridge	Newhall	0.7	0.78
January 17, 1994 Northridge	Rinaldi	0.87	0.38
January 17, 1994 Northridge	Sylmar	0.72	0.58
Average		0.64	0.54

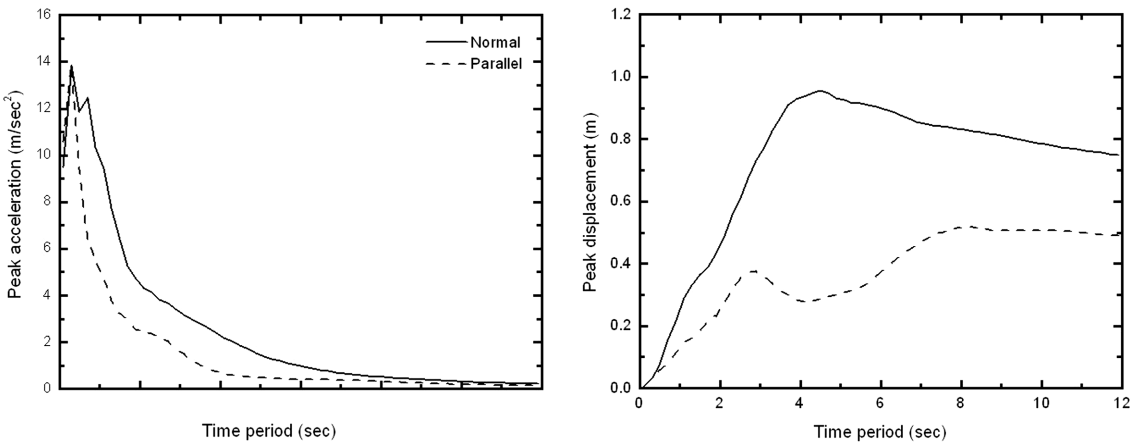


Fig. 3 Average absolute acceleration and displacement spectra for fault normal and fault parallel component of near-fault motions

5. Near-fault earthquake ground motions

Ground motions generated from earthquakes differ from one another in magnitude, source, characteristics, distance and direction from the rupture location and local soil conditions. It has been observed that the motions recorded near the fault of major earthquakes contain large displacement pulses ranging from 0.5 m to more than 1.5 m with peak velocities of 0.5 m/sec or higher (Jangid and Kelly 2001). For the present study, six pairs of the near-fault earthquake motion are used to study the performance of sliding systems. The peak acceleration of these selected near-fault motions are shown in Table 1. It is observed that the peak acceleration of fault normal component is relatively higher than that of fault parallel component. The average absolute acceleration and displacement spectrum of these motions for 5 percent damping is shown in Fig. 3. For low periods (in the range 0 to 0.3 sec) the average spectral acceleration values of the fault normal and parallel component is almost same. Also, the maximum value of the spectra is the same for both components occurring at the same period. For longer periods (in the range of 2 to 8 sec) the spectral acceleration and displacement component of fault normal component is significantly larger than the fault parallel component. This implies that the response of base-isolated structures (which are flexible system) will be mainly contributed by the fault normal component of the near-fault motion.

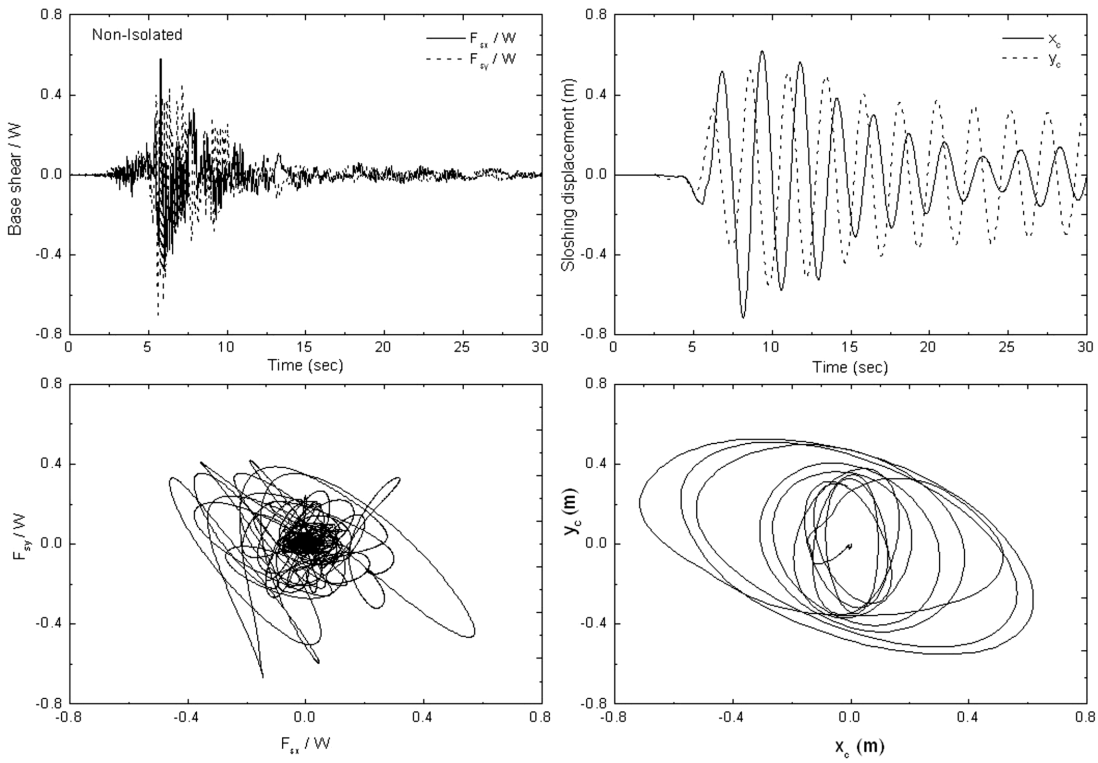


Fig. 4 Time variation response of non-isolated slender tank under Imperial Valley, 1979 (Array #5) near-fault earthquake motion

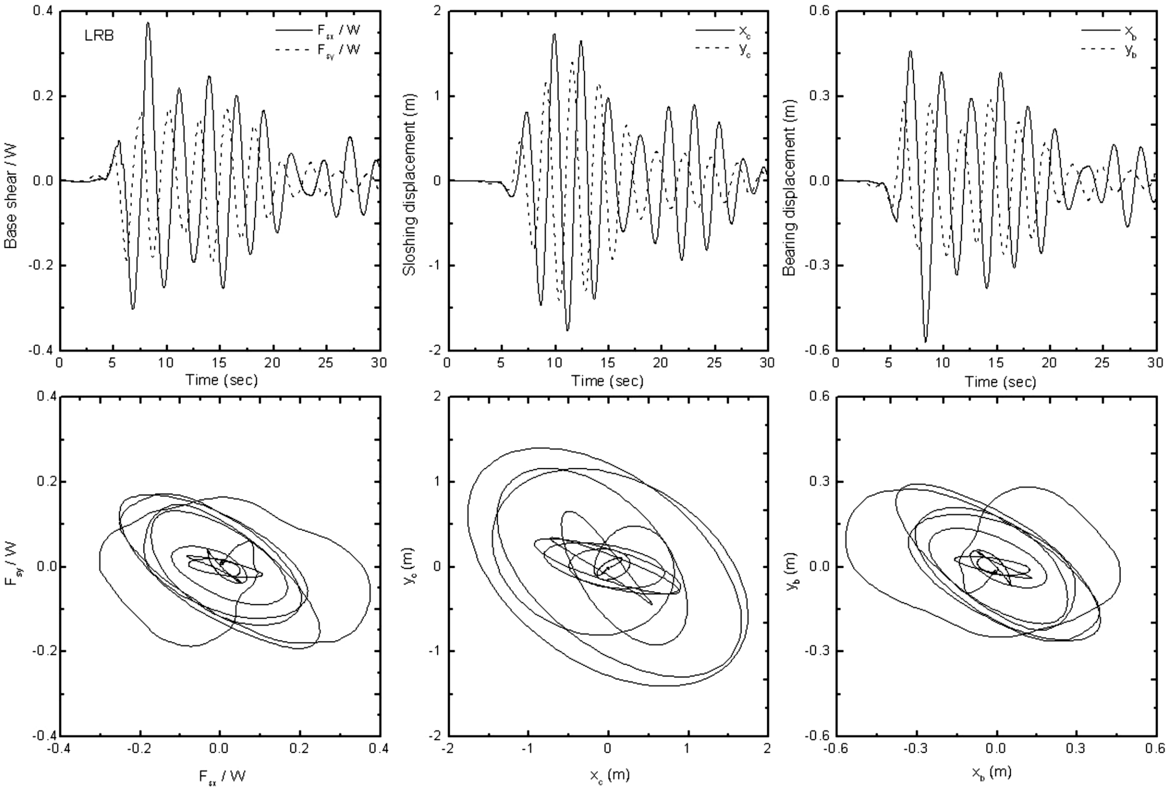


Fig. 5 Time variation response of slender tank isolated with LRB system under Imperial Valley, 1979 (Array #5) near-fault earthquake motion ($T_b = 2$ sec and $\xi_b = 0.1$)

6. Numerical study

Seismic response of the liquid storage tanks isolated by the elastomeric bearing and sliding system is investigated under near-fault earthquake motion. Initially, the fault normal and parallel components are applied in the x- and y-direction of the tank, respectively. The response quantities of interest are base shear, sloshing displacement and bearing displacement in two horizontal directions of the tank. The parameters, which characterize the model of liquid storage tank, are the height of liquid in the tank (H), aspect ratio (S), damping ratio of the sloshing mass (ξ_c) and damping ratio of the impulsive mass (ξ_i). For the present study, the parameter S is varied whereas $H = 10$ m, $\xi_c = 0.5$ percent and $\xi_i = 2$ percent are kept constant. For the tanks with steel wall, the modulus of elasticity is taken as $E = 200$ GPa and the mass density, $\rho_s = 7,900$ kg/m^3.

The time variation of base shear and sloshing displacement of non-isolated slender tank is shown in Fig. 4. The figure indicates that the peak base shear and sloshing displacement are almost same for the fault parallel and normal components of earthquake motion. However, the response due to normal component is marginally higher than the parallel component. The time variation of corresponding response quantities of the tank isolated by the LRB system is shown in Fig. 5. The parameters of the LRB system considered are $T_b = 2$ sec and $\xi_b = 0.1$. It is observed from the figure

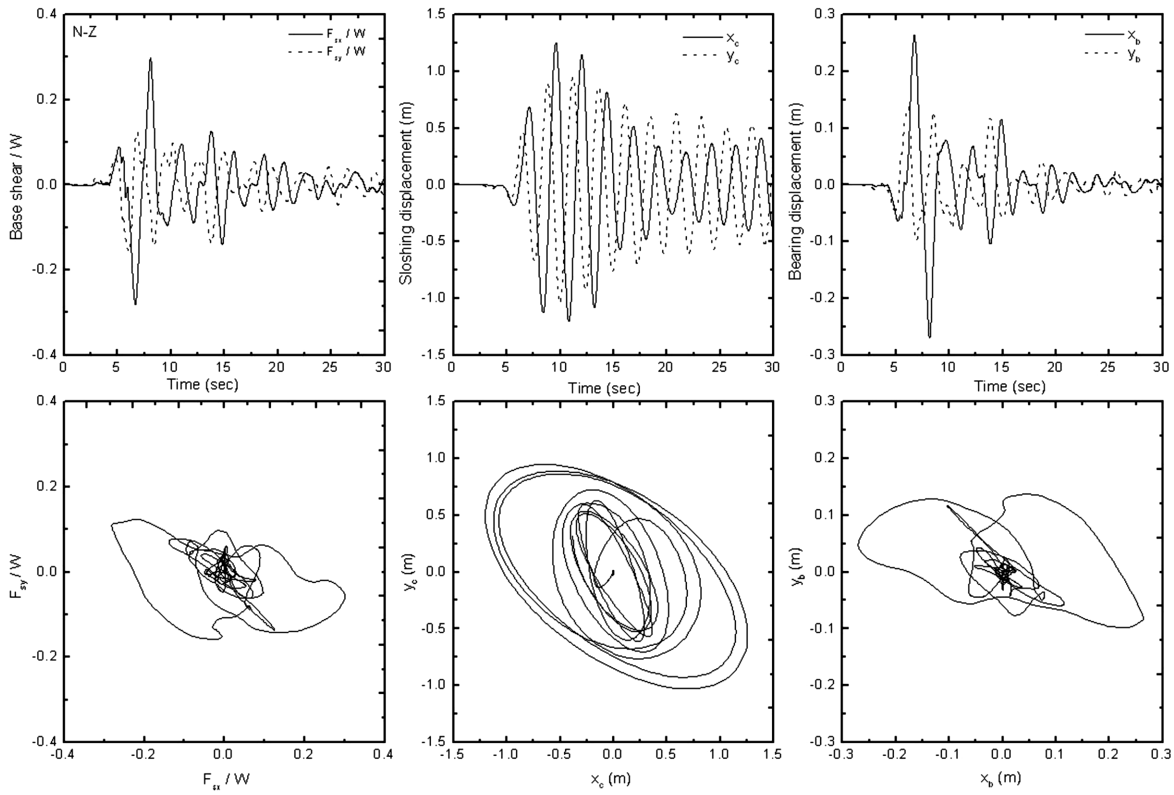


Fig. 6 Time variation response of slender tank isolated with N-Z system under Imperial Valley, 1979 (Array #5) near-fault earthquake motion (T_b = 2.5 sec, ξ_b = 0.1 and F_y = 0.05 W)

that due to base isolation there is significant reduction in the base shear (compare with Fig. 4). However, there is increase in the sloshing displacement due to base isolation. Further, the peak base shear and bearing displacement are significantly higher for normal component in comparison to the parallel component. Similar effects of base isolation and near-fault motion are depicted in Figs. 6 and 7 showing the response of the tank isolated by N-Z (T_b = 2.5 sec, ξ_b = 0.1 and F_0 = 0.05) and FPS (T_b = 2.5 and μ = 0.05), respectively.

The Fig. 8 shows the ratio of peak average resultant to the peak average normal component of base shear, sloshing displacement and bearing displacement against different aspect ratios of the tank. It is clear from the figure that, in case of isolated tanks the peak average resultant base shear and bearing displacement are not more than 5 percent of the peak average normal component of base shear and bearing displacement of near-fault earthquake ground motions. Thus, the peak average resultant base shear and bearing displacement under near-fault motions may be obtained solely from normal component with addition of about 5 percent to incorporate the contribution from the parallel component. The resultant sloshing displacement can also be obtained by the similar rule in the range of aspect ratio from 0.75 to 2.5. However, for broad tanks with aspect ratio in the range of 0.25 to 0.75 an increase of the order of 10 percent is required to find the resultant sloshing displacement from the fault normal component.

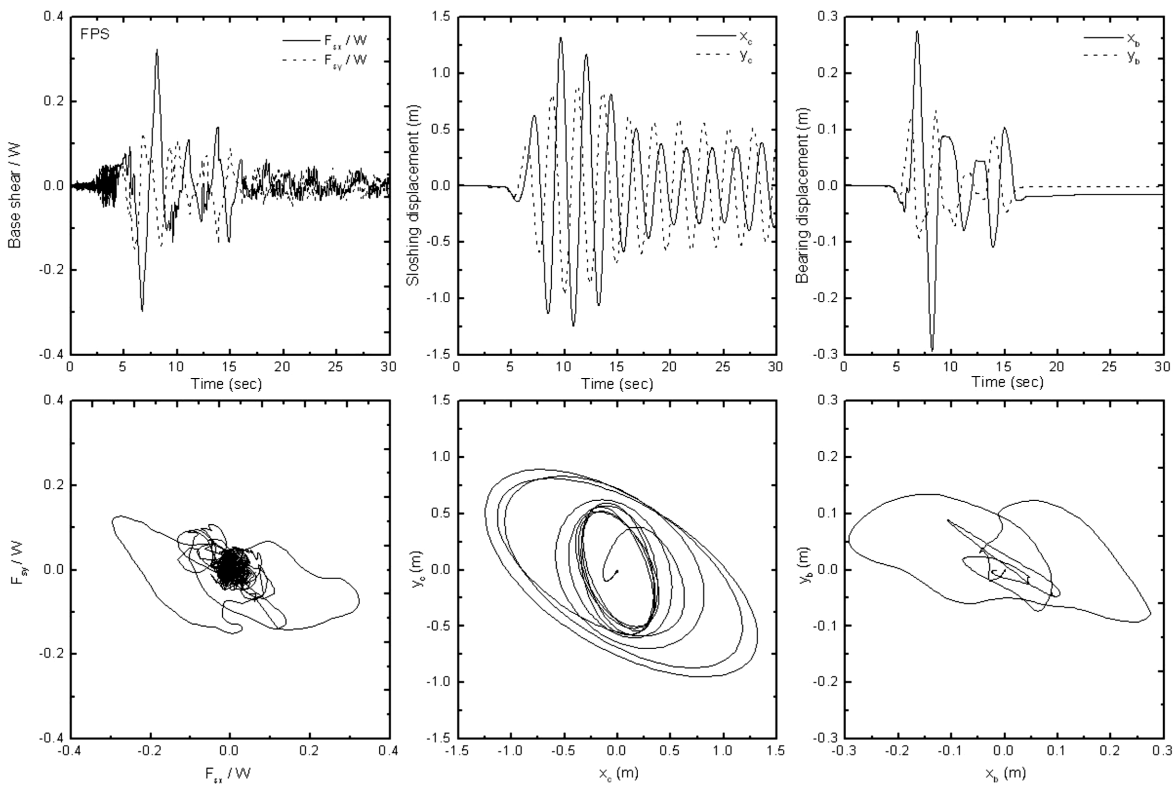


Fig. 7 Time variation response of slender tank isolated with FPS system under Imperial Valley, 1979 (Array #5) near-fault earthquake motion (T_b = 2.5 sec and μ = 0.05)

The Fig. 9 shows the variation of average peak base shear, sloshing displacement and bearing displacement of the tank isolated by the LRB system under the normal components of near-fault earthquake ground motions against bearing damping. The responses are shown for both broad (S = 0.6) and slender (S = 2) tanks with the damping ratio, ξ_b varied from 0.05 to 0.6 for three bearing periods (i.e., T_b = 1.5, 2 and 2.5 sec). The figure indicates that the sloshing and bearing displacement decreases as the bearing damping increases for both broad as well as slender tank. On the other hand, the base shear first decreases, attains the minimum value and than increases with the increase of the bearing damping. This implies that there exists an optimum bearing damping for which the base shear in the isolated tanks attains the minimum value.

From Fig. 9, it is also observed that the base shear decreases with the increase of isolation period (compare the response for different T_b values). Thus, the effectiveness of LRB increases with the increase of its flexibility. On the other hand, the bearing displacements are also relatively higher for the higher values of isolation period. Thus, the earthquake forces transmitted to the tank system can be reduced at the expense of increasing displacement of the LRB. However, the displacement of the LRB has a practical limitation. Therefore, in designing the LRB a compromise shall be made between transmitted earthquake forces and relative bearing displacements.

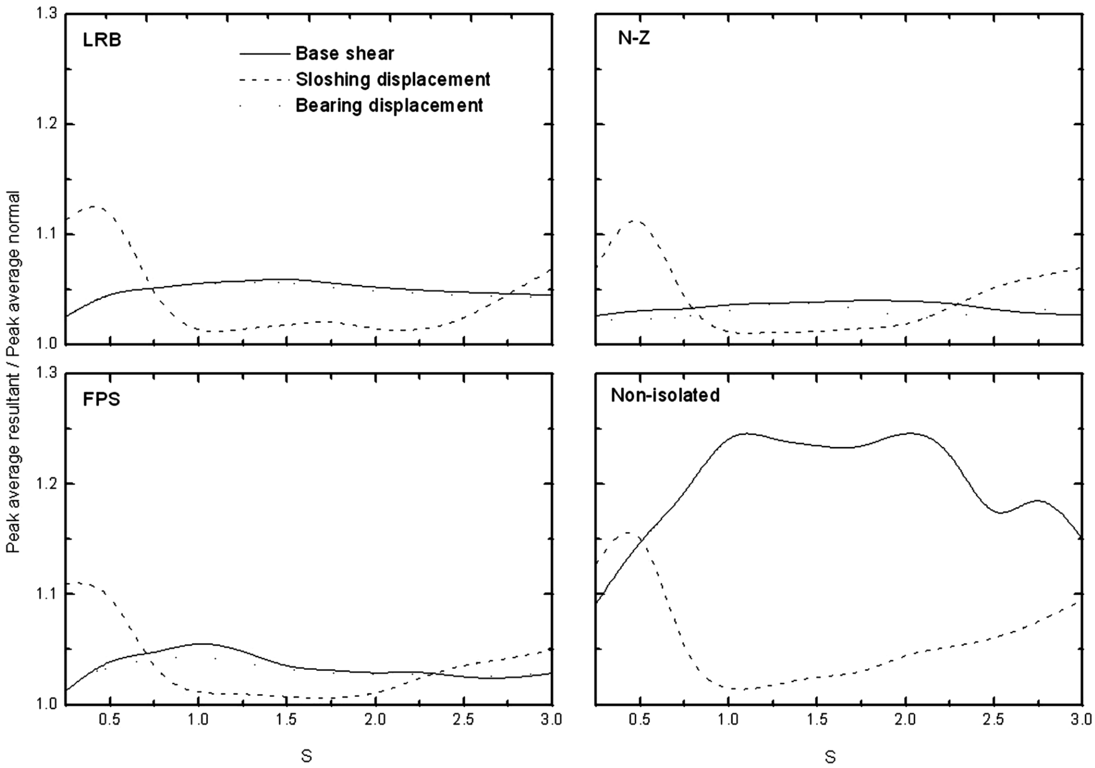


Fig. 8 Ratio of peak average resultant to peak average normal response of tank; isolated with various isolation systems against aspect ratio

6.1 Comparative performance of different isolation systems

In this section, a comparative performance of five different isolation systems is studied under the normal component of near-fault motions. Fig. 10 shows the variation of the peak average response of liquid storage tank isolated with different isolation systems against tank aspect ratio, S. The various isolation system considered are LRB (T_b = 2 sec and ξ_b = 0.1), N-Z (T_b = 2.5 sec, ξ_b = 0.1 and F_0 = 0.05), FPS (T_b = 2.5 sec and μ =0.05), R-FBI (T_b = 4 sec, ξ_b = 0.1 and μ =0.04) and EDF (T_b = 2 sec, ξ_b = 0.05 and μ = 0.2) system. The parameters of the various isolation systems are considered as that recommended in the past for their optimal performance and also similar range of the parameters were selected in the past studies for comparative performance of different isolation systems (Lin *et al.* 1989, Su *et al.* 1990). The Fig. 10 indicates that, in case of R-FBI system, as aspect ratio increases the base shear reduces but the bearing displacement increases in comparison to the other systems. On the other hand, in case of the EDF system the base shear, sloshing displacement and bearing displacement are relatively less as compared to the other isolation systems. This implies that the EDF system is very effective isolation system under near-fault locations as it provides lesser bearing displacement as well as base shear. Thus, under the typical selected isolator parameters, the EDF system is found to be more effective for liquid storage tanks under near-fault motions.

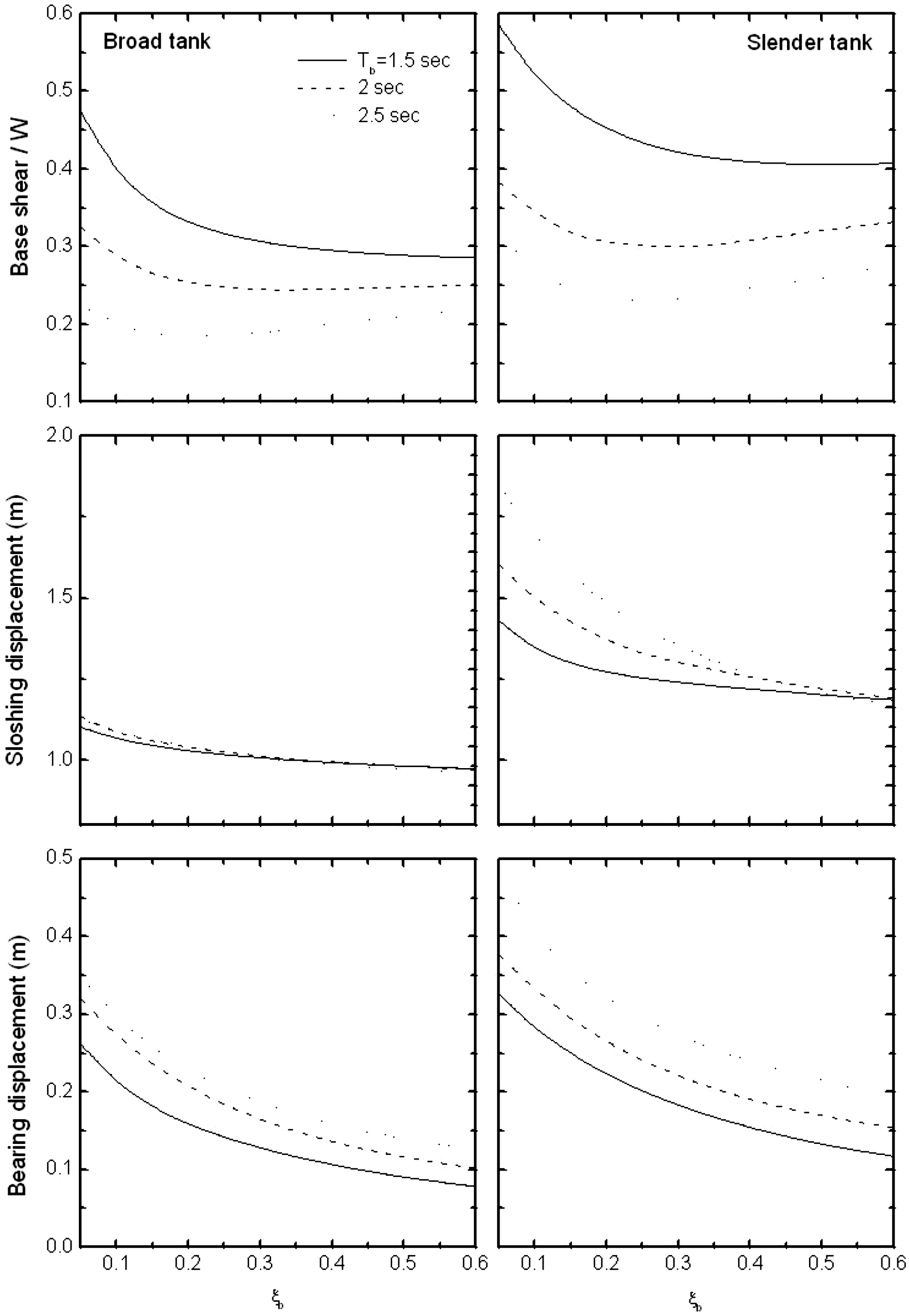


Fig. 9 Response of broad and slender tank isolated with LRB system against bearing damping for bearing time period

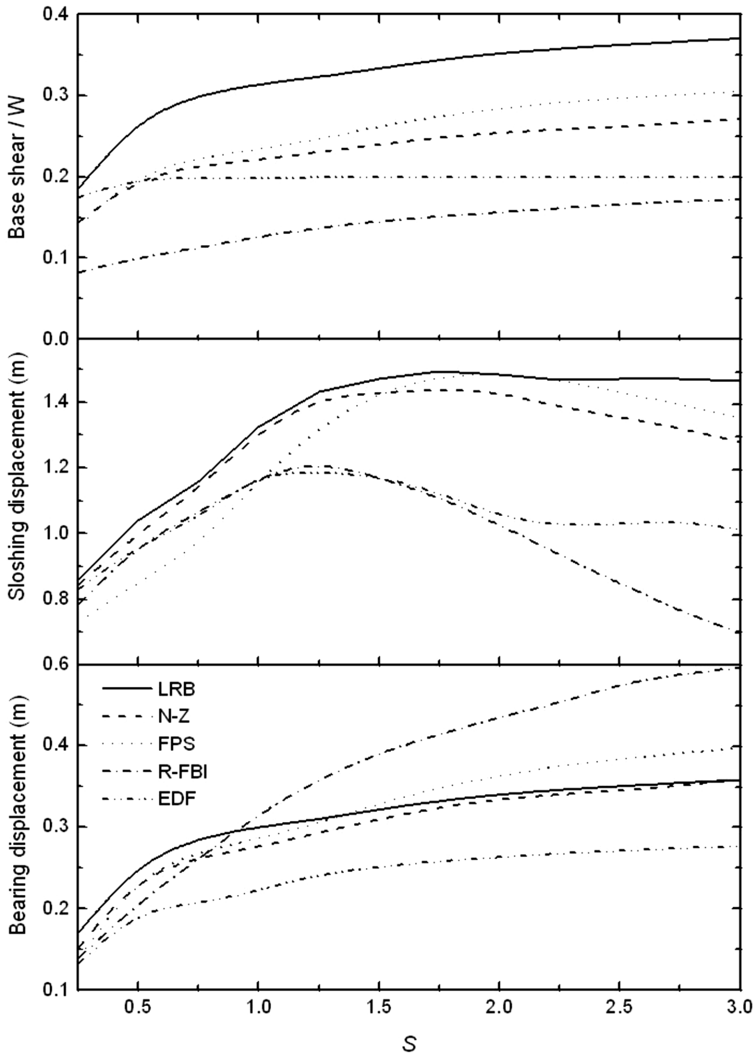


Fig. 10 Comparison of peak average response of tank isolated with different systems under normal component of near-fault motions

6.2 Response of isolated tanks under cycloidal pulse

Figs. 11 and 12 show the response of tanks under normal component of the near-fault motions Imperial Valley, 1979 (Array #5) and Northridge, 1994 (Sylmar) using acceleration time history and cycloidal pulses associated in that motions respectively (left side plots shows the response of tank for acceleration history and right side plots shows the response for pulse motion). The response of tank is obtained for different aspect ratios, S (i.e., 0.25 to 3) and for five different isolation systems (i.e., LRB, N-Z, FPS, R-FBI and EDF systems). By comparing the responses obtained from acceleration history and pulse motion it can be concluded that the results obtained under pulse type motion are close to that of results obtained from acceleration history. Hence, the satisfactory

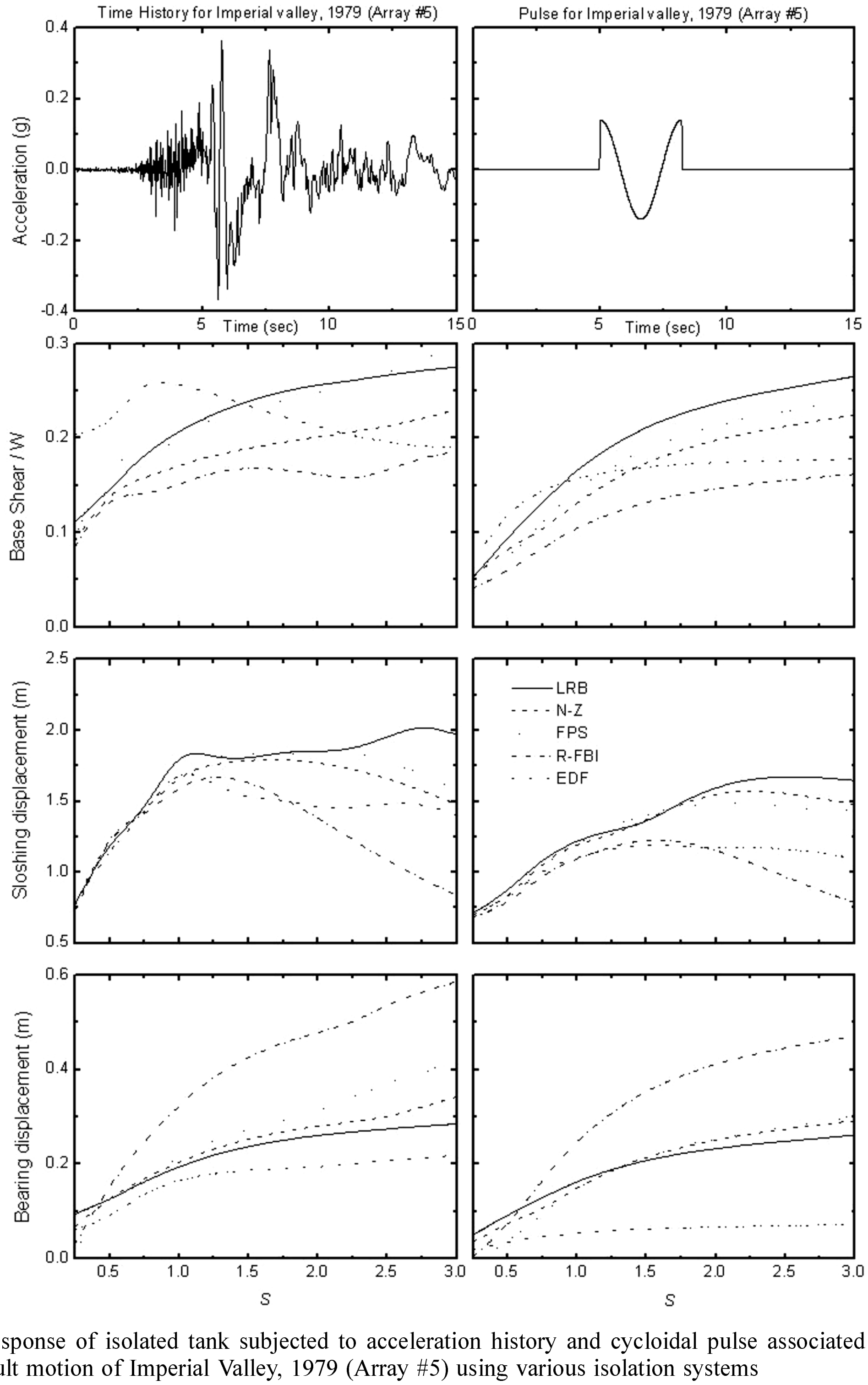


Fig. 11 Response of isolated tank subjected to acceleration history and cycloidal pulse associated with near-fault motion of Imperial Valley, 1979 (Array #5) using various isolation systems

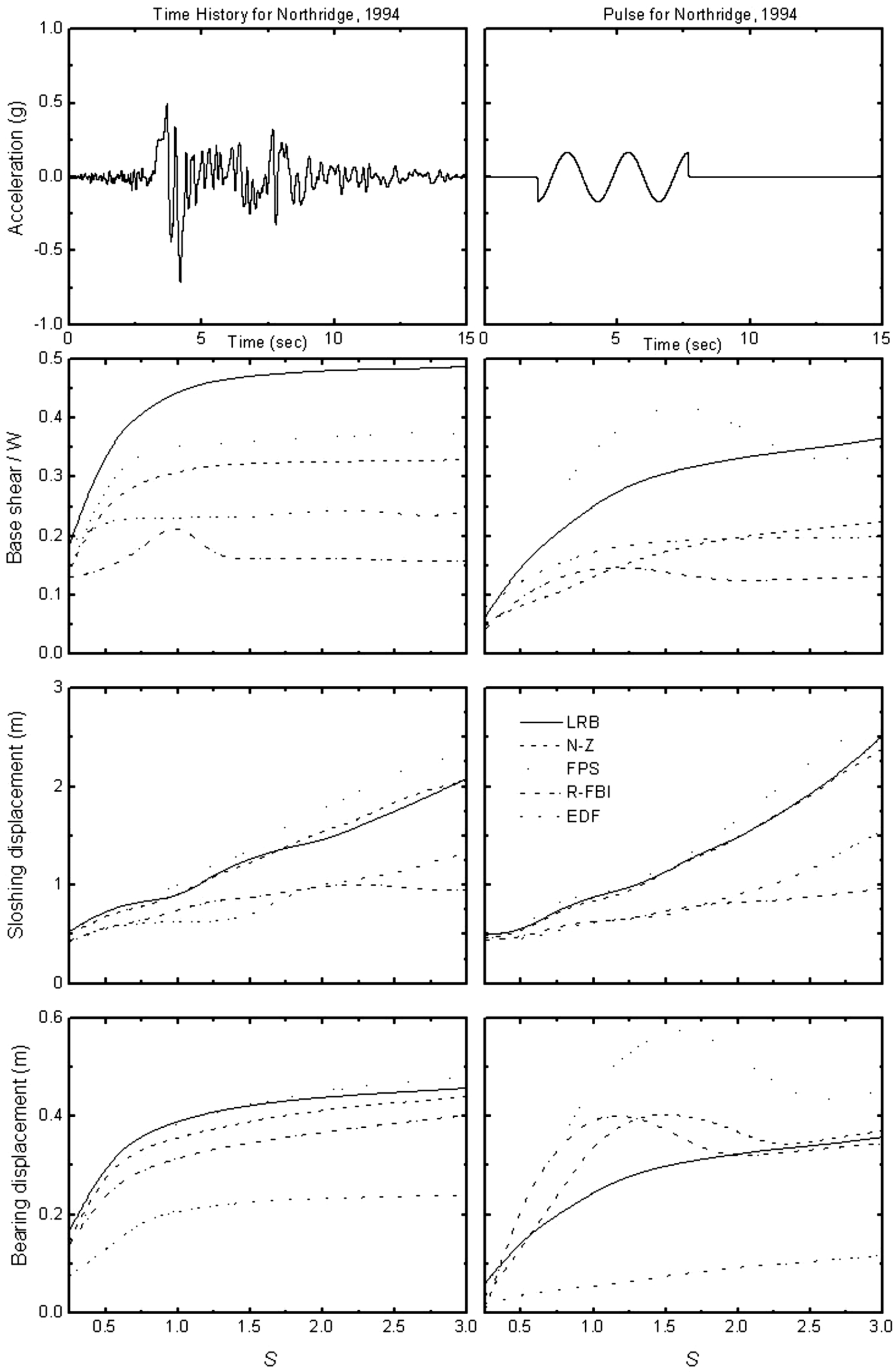


Fig. 12 Response of isolated tank subjected to acceleration history and cycloidal pulse associated with near-fault motion of Northridge, 1994 (Sylmar) using various isolation systems

responses can be obtained by analyzing the tank under simple pulse type motion instead of acceleration history. Further, as observed earlier, the EDF system performs better under cycloidal pulse in comparison to other isolation systems.

7. Conclusions

Seismic response of the liquid storage tanks isolated by the elastomeric bearing and sliding system is investigated under near-fault earthquake motion. The fault normal and parallel components of near-fault motion are applied in two horizontal direction of the tank. The continuous liquid mass of the tank is modeled as lumped masses known as sloshing mass, impulsive mass and rigid mass. A parametric study is carried out to study the effects of important system parameters on the effectiveness of seismic isolation for liquid storage tanks under near-fault motion. Further, a comparative performance of different isolation systems for liquid storage tanks is also studied. From the trends of the results of the present study, following conclusions can be drawn:

1. Base isolation is quite effective in reducing the peak base shear of the liquid storage tanks under near-fault earthquake ground motion. However, there is significant increase in the sloshing displacement of the tank liquid due to isolation under near-fault motion.
2. The peak response of isolated tank is mainly governed by the fault normal component and the contribution of fault parallel component is significantly less. The peak resultant response can be obtained from the fault normal component by increasing about 5 percent to tank into account the contribution of the parallel component.
3. The effectiveness of base isolation increases with the increase of the flexibility of isolation systems.
4. There exists an optimum value of the isolation damping for which the base shear in the tank is the minimum. Increase of isolation damping beyond the optimum value will decrease the bearing and sloshing displacement but it increases the base shear.
5. Under the typical selected isolator parameters, the EDF system is found to be more effective isolation system for liquid storage tanks under near-fault locations.
6. The response of isolated tanks obtained by simple pulse type motion and that of acceleration history are not differ much from each other. Therefore, the satisfactory response can be obtained by analyzing the tank under simple cycloidal pulse type motion instead of complete acceleration history.

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