Response of Elevated Liquid Storage Steel Tank with Variable Frequency Pendulum Isolator

Poonam S. Sutar, S. C. Potnis, S. K. Bhor, Vinayak Sutar

Abstract*— *The seismic response of liquid storage steel tanks with the variable frequency pendulum isolator (VFPI) is compared with that of the same liquid storage steel tanks isolated using the linear elastomeric bearings under real earthquake ground motion. In order to measure the effectiveness of isolation system, the seismic response of isolated steel tanks is compared with that of the non-isolated steel tanks.

Two types of isolated tank models are considered in which the bearings are placed at the base and top of the steel tower structure. The seismic response is obtained by the Newmark's step-by-step method. The response of two types of tanks, namely slender and broad tanks, is obtained and a parametric study is carried out to study the effects of important system parameters on the effectiveness of seismic isolation. The various important parameters considered are the tank aspect ratio, the time period of tower structure, damping and the time period of isolation system. Further, a parametric study has been carried out to examine the behavior of liquid storage steel tanks isolated with VFPIs. The important parameters considered are the friction coefficient of the VFPI, the Frequency Variation Factor (FVF) of the VFPI and the tank aspect ratio. It is observed from proposed analysis that the seismic response of elevated steel tanks accurately with significantly less computational efforts. It is concluded that seismic response, viz. the base shear, the sloshing displacement and the impulsive displacement, of liquid storage steel tanks during earthquake ground motions can be controlled with the installation of the VFPI. The linear elastomeric bearings and VFPI isolators has almost the same effect in the tank to the far-field ground motions. MATLAB software has been used for analysis and solving all dynamic equations of motion. The isolation is very effective in reducing the seismic response of elevated liquid storage tanks.

Index Terms*—*aspect ratio, isolation system, liquid storage steel tank, system parameters.

I. INTRODUCTION

Liquid storage steel tanks are very important structures since they have widely use in industries and nuclear power plants. The weight of storage tanks varies in time due to variable liquid storage level, and they may contain low-temperature (e.g., Liquefied Natural Gas (LNG)) or corrosive substances. Typical damage at tanks during past earthquakes were occurred like buckling of tank wall, toppling of tower structure ,failure of piping system and uplift of the anchorage system. The tanks are manufactured from small to very big size. The earthquake motion excites the liquid contained in the tank.

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A part of the liquid moves independent of the tank wall motion is termed, as convective or sloshing while, another part of the liquid, which moves in unison with rigid tank wall, is known as impulsive mass [3]. If the flexibility of the tank wall is considered than the part of the impulsive mass moves independently while remaining accelerates back and forth with tank wall known as rigid mass.

The accelerating liquid as sloshing, impulsive and rigid masses induces hydrodynamic pressures on the tank wall of liquid storage tanks which generates design forces such as base shear and overturning moment. Seismic isolation technology is one of the best alternatives for protecting liquid storage steel tanks against severe earthquakes.

II. STRUCTURAL MODEL OF ISOLATED LIQUID STORAGE TANK

Fig. 1(a) shows a structural model of liquid storage cylindrical tank mounted on steel tower structure, which is fixed to the ground. The isolators are placed by two techniques in elevated tank, namely, by placing the isolators between the base of tower structure and foundation (isolated model-I, Fig. 1(b)) and by placing the isolators between bottom of the liquid container and top of the tower structure (isolated model-II, Fig. 1(c)).Tower structure is considered as a supporting system to the tank. The entire liquid mass vibrates in three distinct patterns during the excitation as

Sloshing, impulsive and rigid masses (m_c, m_i and m_r)

Equivalent spring stiffness constants (k_c and k_i)

Damping constants of the sloshing and impulsive masses (c_c and c_i)

Absolute displacements of sloshing mass, impulsive mass and tower drift (u_c, u_i and u_t)

The geometrical parameters: liquid height H, radius, R and average thickness of tank wall, t_h.

The non-dimensional parameters Y_c, Y_i, Y_r and P are functions of the aspect ratio of the tank, S, which are expressed as [3]

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

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

$$Y_c = m_c / m \quad (1)$$

$$Y_i = m_i / m \quad (2)$$

$$Y_r = m_r / m \quad (3)$$

$$m = \pi R^2 H \rho_w \quad (4)$$

Where ρ_w is the mass density of liquid.

The natural frequencies of sloshing mass, ω_c and impulsive mass, ω_i are given by the following expression

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

$$\omega_c = \sqrt{1.84\,(g/R)\tanh(1.84\,S)} \tag{6}$$

Where P is dimensionless parameter, E and ρ_s are the modulus of elasticity and density of tank wall, respectively; g is the acceleration due to gravity.

The equivalent stiffness and damping of the sloshing and impulsive masses are expressed as [3]

$$k_c = m_c\,\omega_c^2 \tag{7}$$

$$k_i = m_i\,\omega_i^2 \tag{8}$$

$$Cc = 2\,\xi_c\,m_c\,\omega_c \tag{9}$$

$$C_i = 2\,\xi_i\,m_i\,\omega_I \tag{10}$$

Where ξ_c and ξ_i are damping ratio of sloshing mass and impulsive mass respectively

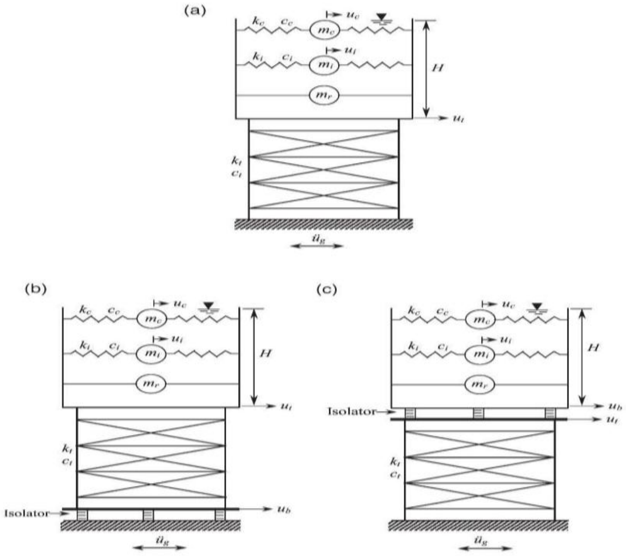

Fig.1. Structural model of elevated liquid storage steel tank: (a) non-isolated, (b) isolation at bottom (isolated model-I), (c) isolation at top (isolated model-II).

B Governing Equations of Motion

The equation of motion of elevated liquid storage tank subjected to uni-directional earthquake ground motion are expressed in the matrix form as,

$$[m]\{\ddot{x}\} + [c]\{\dot{x}\} + [k]\{x\} = -[m]\{r\}\,\ddot{u}_g \tag{11}$$

Where, {x} = displacement vector, {m} = mass matrix,
{c}= damping matrix,{k}= stiffness matrix
{r}= influence coefficient vector

III. NON-ISOLATED TANK

The displacement vector is given by $\{x\} = \{x_c, x_i, x_t\}^T$

$x_c = u_c - u_t$ (the relative displacement of the sloshing mass) ,

$x_i = u_i - u_t$ (the relative displacement of impulsive mass);

$x_s = u_t - u_g$ (the tower displacement relative to ground i.e. tower drift),

The matrices [m], [c], [k] and the vector {r} for non-isolated tank are expressed as [6]

$$[m] = \begin{bmatrix} m_c & 0 & m_c \\ 0 & m_i & m_i \\ m_c & m_i & M + m_b \end{bmatrix} \tag{12}$$

$$[c] = \mathrm{diag}\,[c_c, c_i, c_t] \tag{13}$$

$$[k] = \mathrm{diag}\,[k_c, k_i, k_t] \tag{14}$$

$$\{r\} = \{0, 0, 1\}^T \tag{15}$$

Where $M = m_c + m_i + m_r$ is the effective mass of the tank and m_b is equal to $0.05m$.

The stiffness K_t and damping, C_t of the tower structure are based on the assumption of equivalent single –degree-of-freedom system which are defined as

$$k_t = (2\pi/T_t)^2\,(M + 0.05m) \tag{16}$$

$$c_t = 2\xi_t\,(M + 0.05m)\,\omega_t \tag{17}$$

Where, T_t = time period of the tower structure
ξ_t = damping ratio of the tower structure

IV. ISOLATED BY THE LINEAR ELASTOMERIC BEARING

A. Isolated model – I

The displacement vector is given by: $\{x\} = \{x_c, x_i, x_t, x_b\}^T$

$x_c = u_c - u_t$ (the relative displacement of the sloshing mass) ,

$x_i = u_i - u_t$ (the relative displacement of impulsive mass);

$x_s = u_t - u_b$ (the tower displacement relative to ground i.e. tower drift) and

$x_b = u_b - u_g$ (the relative bearing displacement).

The matrices [m], [c], [k] and the vector {r} for non-isolated tank are expressed as [6]

$$[m] = \begin{bmatrix} m_c & 0 & m_c & m_c \\ 0 & m_i & m_i & m_i \\ m_c & m_i & M + m_b & M + m_b \\ m_c & m_i & M + m_b & M + 3m_b \end{bmatrix} \tag{18}$$

$$[c] = \mathrm{diag}\,[c_c, c_i, c_b, c_t] \tag{19}$$

$$[k] = \mathrm{diag}\,[k_c, k_i, k_b, k_t] \tag{20}$$

$$\{r\} = \{0, 0, 0, 1\}^T \tag{21}$$

The stiffness K_b and damping, C_b of the tower structure are

$$k_b = (2\pi/T_t)^2\,(M + 0.15m) \tag{22}$$

$$c_b = 2\xi_b\,(M + 0.15m)\,\omega_b \tag{23}$$

Where, Tb = time period of isolation system
ξ_b = damping ratio of isolation system
ω_b = isolation frequency

B. Isolated model-II

The displacement vector is given by $\{x\} = \{x_c, x_i, x_b, x_t\}^T$

$x_c = u_c - u_b$ (the relative displacement of the sloshing mass) ,

$x_i = u_i - u_b$ (the relative displacement of impulsive mass);

$x_b = u_b - u_t$ (the relative bearing displacement) and

$x_s = u_t - u_g$ (the relative tower displacement).

The matrices [m], [c], [k] and the vector {r} are expressed as [6]

$$[m] = \begin{bmatrix} m_c & 0 & m_c & m_c \\ 0 & m_i & m_i & m_i \\ m_c & m_i & M & M \\ m_c & m_i & M & M + 2m_b \end{bmatrix} \tag{24}$$

$$[c] = \mathrm{diag}\,[c_c, c_i, c_b, c_t] \tag{25}$$

$$[k] = \mathrm{diag}\,[k_c, k_i, k_b, k_t] \tag{26}$$

$$\{r\} = \{0, 0, 0, 1\}^T \tag{27}$$

The stiffness and damping of the isolation system and tower structure are expressed as

$$k_t = (2\pi/T_t)^2\,(M + 0.1m) \tag{28}$$

$$k_b = (2\pi/T_b)^2\,M \tag{29}$$

$$c_t = 2\xi_t\,(M + 0.1m)\,\omega_t \tag{30}$$

$c_b = 2\xi_b M \omega_b$ (31)

the 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 After obtaining the acceleration vector, the base shear is computed,

$F_b = m_c\ddot{u}_c + m_i\ddot{u}_i + (m_r + 0.05m)\,\ddot{u}_t$
(For non-isolated model) (32)

$Fb = mc\ddot{u}c + mi\ddot{u}i + (mr + 0.05m)\,\ddot{u}t + 2mb\ddot{u}b$
(For isolated model – I) (33)

$F_b = m_c\ddot{u}_c + m_i\ddot{u}_i + m_r\ddot{u}_b + 2m_b\ddot{u}_t$
(For isolated model - II) (34)

V. ISOLATED BY VARIABLE FREQUENCY PENDULUM ISOLATOR (VFPI)

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

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + \{F\} = -[M]\{r\}\ddot{u}_g \quad (35)$$

Where, $\{x\} = \{x_c, x_i, x_b\}^T$ are relative displacement vector, and

$\{F\} = \{0, 0, Fx\}^T$ are the frictional force vectors,

$x_c = u_c - u_b$ is the displacement of the sloshing mass relative to bearing displacement;

$x_i = u_i - u_b$ is the displacement of the impulsive mass relative to bearing displacement;

$x_b = u_b - u_g$ is the displacement of the bearing relative to ground;

$[M]$, $[C]$, and $[K]$ = the mass, damping and stiffness matrices of the system,

$\{r\}$ = the influence coefficient vector;

F_x = the frictional force mobilized in the isolator;

$\ddot{x}_g$ = the earthquake ground acceleration;

T = transpose; and over dots indicate derivative with respect to time.

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 system remains in the non-sliding phase ($\dot{x}_b = \ddot{x}_b = 0$), if the frictional force mobilized at the interface of the VFPI is less than the limiting frictional force (i.e., $|F_x| < F_s$). However, the system starts sliding ($\dot{x}_b \neq \ddot{x}_b \neq 0$), as soon as the frictional force attains the limiting frictional force (i.e., $|F_x| = F_s$). Due to the highly non-linear behaviour of the system, a very small time steps of the order of 0.0001 sec is selected such that it is at least one-hundredth of the impulsive period of the liquid storage tank. To stop the Newmark iterations in each time step, the following convergence criterion is selected

$$\text{Relative error} = \frac{|(\Delta x)_{j+1}| - |(\Delta x)_j|}{|(\Delta x)_j|} \leq \varepsilon$$

where Δx is the incremental relative displacement; j is the iteration number; and ε is a small threshold parameter. The convergence parameter ε is taken as 10-5 in each time step.

VI. DESCRIPTION OF VFPI

A new isolator called the VFPI [11] incorporates the advantages of both the friction pendulum system (FPS) and Pure-Friction (P-F) isolators (Fig 2). In this isolator, the shape of the sliding surface is non-spherical. Its geometry has been derived from the basic equation of an ellipse, with its semi-major axis being a linear function of sliding displacement. This is equivalent to an infinite number of ellipses continuously transforming into one another such that the semi-major axis is larger for larger sliding displacement. The performance of the VFPI is found to be very effective for a variety of excitation and structural characteristics. The details and operation of VFPI is almost same as the FPS. The VFPI is relatively flatter than FPS, which results in smaller vertical displacement for similar displacements. This is an additional advantage of the VFPI compared to the FPS since flatter sliding surface will result in the generation of smaller overturning forces in the structure. The most important properties of this system are: (a) its time period of oscillation depends on the sliding displacement and (b) its restoring force exhibits softening behavior. The isolator geometry is such that its frequency decreases with an increase in the sliding displacement and asymptotically approaches zero at very large displacement. As a result, the dominant frequency of excitation and the isolator frequency are not likely to tune.

Sliding surfaces have the parts made of stainless steel, which provides durability and a lentil-shaped articulated slider covered by self lubricating composite liner (Teflon)-based high bearing capacity composite material. During earthquake, the slider and the concave surface of the lower plate maintain contact and consequently a relative uniform stress distribution is assured. For other types of sliding surfaces, limited contact occurs. To prevent this kind of inconvenience, namely to obtain a continuum contact between the slider and the concave plate, it is necessary to insert an elastomeric layer between the slider and the sole. This layer is similar to that used in elastomeric base isolation systems, assuring high portability. So we can obtain a controlled deformation for fit the concave shape of stationary plate. The Rate of change of frequency can be controlled by choosing suitable geometrical parameter. Isolators specially designed for each facility based on the load capacity requirements, earthquake displacement capacity, soil conditions, and the size of the structure being supported. Isolators can be designed to accommodate different magnitude of displacement simply by adjusting the curvature.

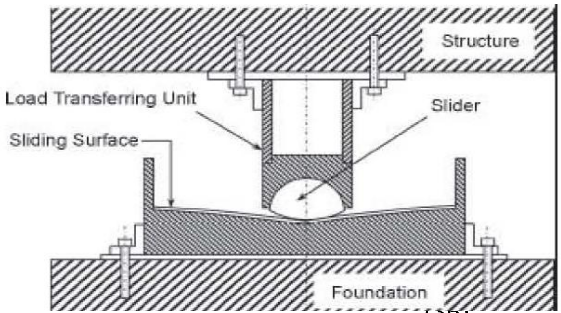

Fig.2. Details of the VFPI

The response of structure with the FPS increases for higher time periods, whereas the response of the VFPI is almost independent of the structural time period. The instantaneous stiffness of the VFPI [11] can be written as:

$k_b(x) = M\,\omega_b^2(x_b)$ (37)

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$$\omega_b^2(x_b) = \frac{\omega b^2}{(1+r)^2\sqrt{1+2r}} \quad (38)$$

$$r = \frac{r_b\, sgn(x_b)}{d} \quad (39)$$

$$\omega_b^{\ 2} = \frac{gb}{d^2} \quad (40)$$

$$T_i = 2\pi\sqrt{\frac{d^2}{gd}} \quad (41)$$

Where, $M = m_c + m_i + m_r$ (the total effective mass of the isolated liquid storage tank);
b and *d* = semi-minor axis and initial value of the semi-major axis (which is greater than zero) of sliding surface;
r = the non dimensional parameter for the sliding surface;
ω_b = the instantaneous frequency of VFPI which depends on the geometry of the sliding surface;
ω_i = the initial frequency of VFPI at zero isolator displacement;
T_i = the initial time period of the VFPI
sgn (x_b) is incorporated to maintain the symmetry of the sliding surface about the central vertical axis. The signum function has a value of +1 for positive value of sliding displacement and -1 for negative value of sliding displacement; the ratio b/d^2 governs the initial frequency of the isolator. Similarly, the value of 1/*d* determines the rate of variation of isolator frequency, and this factor has been defined as frequency variation factor (FVF) [11]. The rate of decrease of isolator frequency is directly proportional to the FVF for a given initial frequency. The limiting value of the frictional force, F_s, to which the sliding system can be subjected in a particular direction, is expressed as:

$$F_s = \mu W \quad (42)$$

Where, μ = the friction coefficient of the sliding system; and $W = Mg$ is the weight supported by the isolator.
Thus, the modeling of VFPI is required the specific value of the two parameters, namely initial time period, *Ti*, and friction coefficient, μ.

VII. NUMERICAL STUDY

A. Liquid storage tank Isolated by the linear elastomeric bearing

Earthquake response of elevated isolated liquid storage steel tanks for slender and broad tanks, is investigated under real earthquake ground motion.. The properties of these tanks are [6]: (i) the aspect ratio, *S* for slender and broad tanks is 1.85 and 0.6, respectively, (ii) the height, *H*, of water filled in the slender and broad tanks is 10 m and (iii) the ratio of tank wall thickness to its radius is taken to be 0.004 for both tanks. The natural frequencies of sloshing and impulsive mass are 0.148 and 5.757 Hz (for broad tank) and 0.291 and 6.738 Hz (for slender tank). The tank wall is considered of steel with modulus of elasticity, *E* = 200 MPa and mass density, ρ_s = 7900 kg/m3. The earthquake response of isolated tank is investigated for two tank models (i.e. models I and II).

B. Liquid storage tank Isolated by VFPI (4.8)

In the study, the seismic response of liquid storage steel tanks isolated with the VFPI is investigated. For comparative and detailed parametric study two different types of tanks, namely the broad and slender tanks, are considered. The VFPI isolator is designed to provide the specific values of two parameters, namely *Ti* and μ based on the parameter *M*. The parameters of VFPI are selected as *b* = 0.04 m and *d* = 0.2 m (FVF 5 per m) so that it has initial time period of 2.0 sec. The coefficient of sliding friction of 0.05 is selected. The tank parameters such as damping ratio of convective mass, ξ_c and the impulsive mass, ξ_i are taken as (5.1) 0.5 and 2%, respectively[17].

VIII. COMPARATIVE STUDY OF PEAK RESPONSES

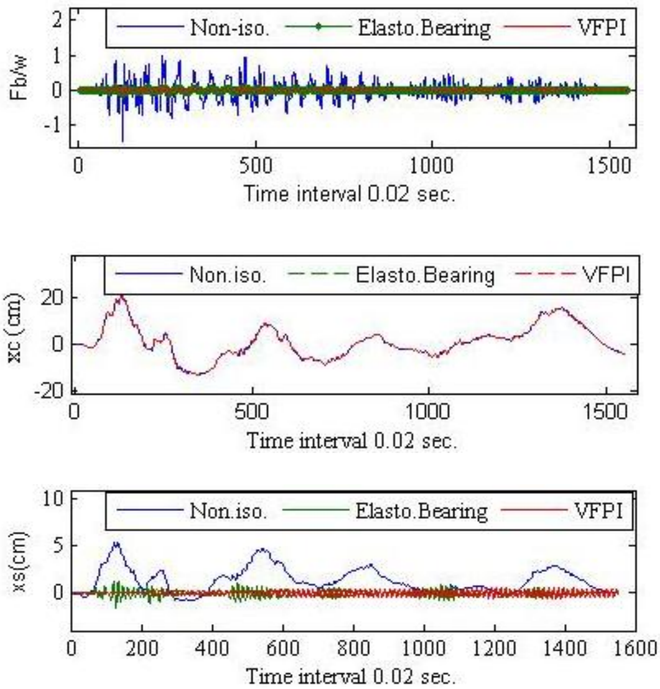
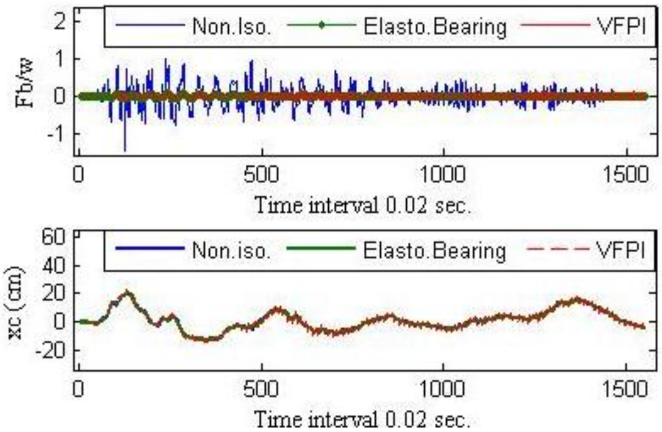


Fig.3 Time variation of slender tank (Model I) under Imperial Valley, 1940 Earthquake



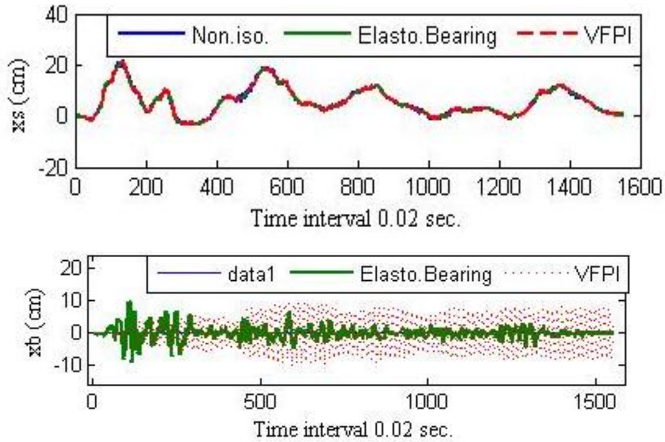


Fig.4 Time variation of slender tank (Model I) under Imperial Valley, 1940 Earthquake

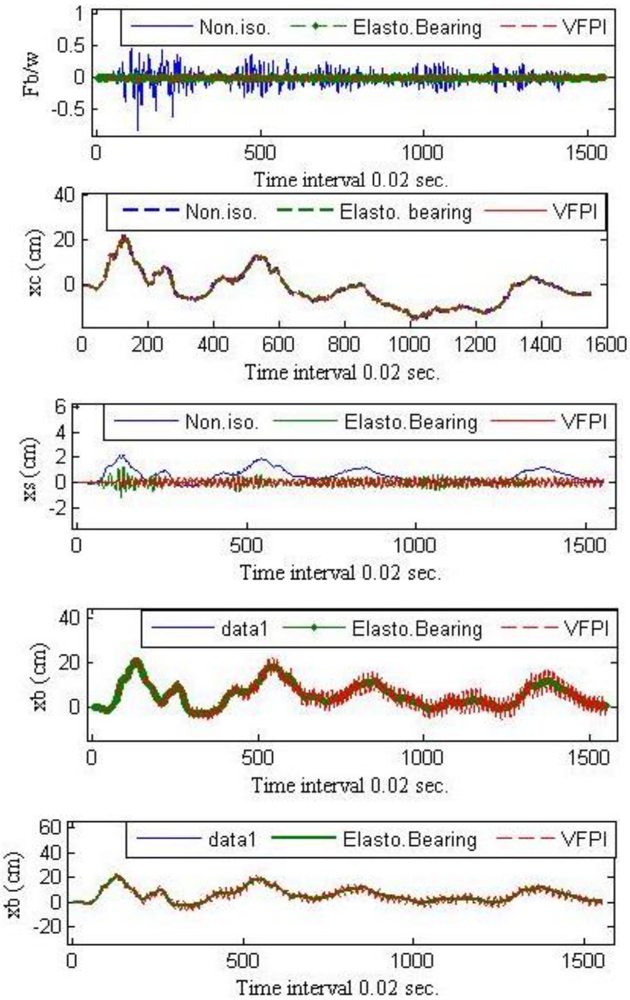
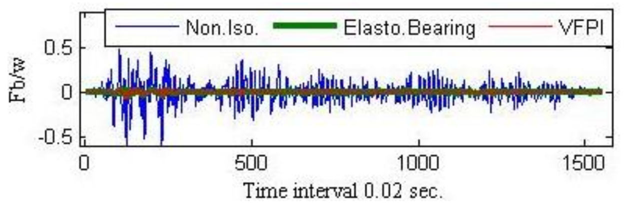


Fig.5 Time variation of Broad Tank (Model I) under Imperial Valley, 1940 Earthquake



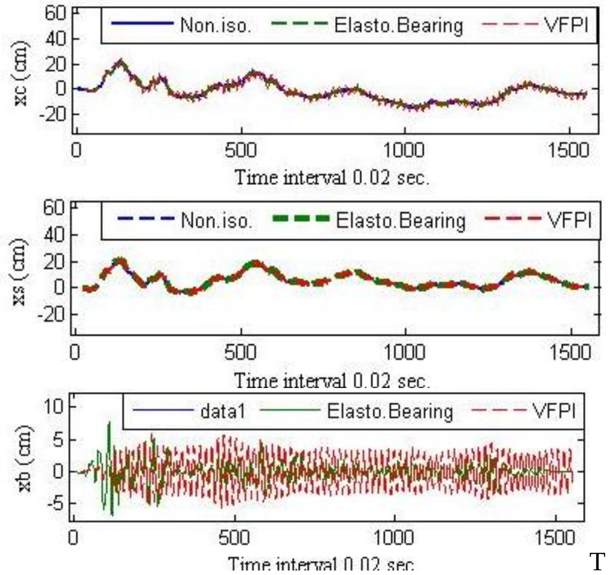


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Fig.6 Time variation of Broad Tank (Model I) under Imperial Valley, 1940 Earthquake

IX. PERCENTAGE REDUCTION IN BASE SHEAR AND TOWER DISPLACEMENT:

I. Percentage reductions in base shear, tower displacement (Slender tank):

Model	Tank condition	F_b/W(%)	x_s (cm)(%)
Model I	Isolated (Elastomeric bearing)	88	76.85
	Isolated (VFPI)	87	90.74
Model II	Isolated (Elastomeric bearing)	91	88.15
	Isolated (VFPI)	83	88.15

II. Percentage reductions in base shear, tower displacement (Broad tank):

Model	Tank condition	F_b/W(%)	x_s (cm)(%)
Model I	Isolated (Elastomeric bearing)	89.58	84.09
	Isolated (VFPI)	87.92	75
Model II	Isolated (Elastomeric bearing)	91.67	80
	Isolated (VFPI)	83.33	80.46

X. CONCLUSION

By using real earthquake motions comparative performance of elevated liquid storage tank by putting the base isolation system at top and bottom of the supporting tower is investigated. The earthquake response of isolated tanks is compared with non isolated tanks to measure the effectiveness of the isolation.

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The base shear of elevated liquid storage tank is significantly reduced due to isolation the base shear is mainly dominated by the impulsive and rigid mass components.

* The drift of steel tower is significantly reduced due to isolation.
* The peak earthquake response of elastomeric bearing of model-I is slightly more than the response obtained by the isolated model- II. The models provide the same effectiveness of base isolation.
* The peak sloshing displacement of slender tank is increased due to isolation effect while for broad tank it has no such influence.
* The base shear, the sloshing displacement and the impulsive displacement during ground motions can be controlled by installation of the VFPI in liquid storage tanks.
* The VFPI is found to be more effective for slender tanks in comparison to the broad tanks.
* The sloshing and impulsive displacement in slender tanks isolated with the VFPI are less than that of the broad tanks isolated with the VFPI whereas the isolator displacement in the slender tanks is more than that of the broad tanks.
* The isolation by the VFPI and elastomeric bearing has almost the same effect in the tank to the far-field ground motions.
* VFPI isolator is a combination of effective energy dissipation and restoring mechanism.

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