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Numerical Analysis of the Base-Isolated Rectangular Storage Tanks under Bi-directional Seismic Excitation

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Original Research Article

Abstract

Liquid storage tanks are critical elements in the water supply scheme and firefighting system in many industrial facilities for storage of water, oil, chemicals and liquefied natural gas. A common effective method to reduce the seismic response of liquid storage tanks is using base-isolation systems. In this research, the finite element method is used to investigate the seismic behavior of rectangular liquid tanks in three-dimensional domains. The continuous liquid mass of the tank was modeled as lumped masses referred as convective mass, impulsive and rigid mass. The rectangular water tank in two cases base isolated and conventional non-isolated system was selected as a case study. The sloshing displacement and base shear response in two mentioned cases subjected to various ground motions under horizontal components X and Y directions were considered and the results were compared. For this purpose the nonlinear time history analyses of the model were performed. As a result, base isolation was found to be effective in reducing the base shear values, without significantly affecting the sloshing displacements.

Keywords: Seismic response, liquid storage tanks, base isolation, finite element model.

1 Introduction

One of the significant lifeline structures which have become extensively during the recent decades is a liquid storage tank. These structures are widely used in water supply facilities, oil and gas industries and nuclear plants for storage of a variety liquid-like-materials such as oil, liquefied natural gas (LNG) and chemical fluids. It becomes such important to study the liquid storage tank, Heavy damages have been reported when these liquid storage tanks are subjected to earthquakes, some the mentioned report on seismic damage occurred in water tanks due to strong earthquakes such as Niigata in 1964, Alaska in 1964, Park field in 1966, Imperial County in 1979, Coalinga in 1983, Northridge in 1994 and Kocaeli in 1999. Due to this fact in recent years, research on base isolation techniques has made significant progress in the reduction of seismic response of liquid storage tanks.

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Some studies for modeling ground liquid storage tanks and their dynamic response have been performed to acknowledge their reaction [1].

Originally, Housner [2] developed a mathematical model in which the mass of the liquid portion that accelerates with the tank is called as the ‘‘impulsive’’ and the mass of the liquid portion that causes the sloshing motion of the free surface near the tank roof is called as the ‘‘convective’’. Haroun [3, 4] modified the Housner’s model and took into account the flexibility of the tank wall in the seismic analysis. Chen and Kianoush [5] studied on Generalized SDOF system for seismic analysis of concrete rectangular liquid storage tanks, comparing the results obtained with those obtained using the finite element method from the previous investigation showed that the proposed method can provide sufficiently accurate results. This study also recommended that the effect of the flexibility of a tank wall should be considered in the calculation of hydrodynamic pressures for concrete rectangular tanks. Kianoush and Ghaemmaghami [6] investigated on the effect of earthquake frequency content on the seismic behavior of concrete rectangular liquid tanks using the finite element method incorporating soil–structure interaction. Chalhoub and Kelly [7,8] observed that the sloshing response increases slightly, but the total hydrodynamic pressures decrease substantially due to base isolation of the tanks. Kim and Lee [9] experimentally investigated the seismic performance of liquid storage tanks isolated by laminated rubber bearings under unidirectional excitation and have shown that the isolation is effective in reducing the dynamic response. Also, Liang and Tang [10] were investigated the effect of base-isolation on the seismic response of liquid tanks. Through different isolation methods, Malhotra [11,12] studied the dynamic behavior of base-isolated liquid storage tanks and concluded that base-isolation was efficient in decreasing the response of the tanks in comparison with those of the conventional fixed base. For two steel tanks (one broad and one slender), they [11,12] examined the effects of base-isolation on both of impulsive and convective components of hydrodynamic pressure. Shrimali and Jangid [13,14] observed that the seismic response of isolated tank is insensitive to interaction effect of the bearing forces. Shekari and Khaji [15] investigated on the numerical seismic response of liquid storage tanks isolated by bilinear hysteretic bearing elements under long-period ground motions.

2 Mathematical Approach

2.1 Governing Equations in Liquid Domain

In this investigation, it is assumed that the fluid is ideal, inviscid and incompressible, and irrotational flow field, the momentum formula is given by equation 1:

$$u = \frac{\partial \emptyset}{\partial x} \quad v = \frac{\partial \emptyset}{\partial y} \qquad\qquad w = \frac{\partial \emptyset}{\partial z} \tag{1}$$

The governing equation of liquid motion is represented by the Laplace equation, where $\emptyset$is the velocity potential and x, y, z are the position vector.This formula is given by equation 2:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \;\; Or \nabla^2 \emptyset = 0 \tag{2}$$

Dynamic boundary condition of the free surface can be represented in general format by the following equation which accounts for the surface sloshing also [16,17]:

$$\frac{\partial^2 \emptyset}{\partial t^2} + g\frac{\partial \emptyset}{\partial z} = 0 \tag{3}$$

However, in the present study the free surface sloshing is neglected and the pressure is assumed to be zero at the water surface with some approximations.

Boundary condition of the fluid–structure interface formula is given by equation 4, [15]:

$$\frac{\partial \emptyset}{\partial n} = v_n(t) \tag{4}$$

In which g is the acceleration gravity, and $v_n(t)$the relative normal fluid velocity at the tank wall at time t.

2.2 Structural Model of Liquid Storage Tank

Fig. 1 shows the idealized structural model of liquid storage tank mounted on isolation system. The lead-rubber bearings are installed between the base and foundation of the tank for isolation. The contained continuous liquid mass is lumped as convective, impulsive and rigid masses referred as m_c, m_i and m_r, respectively. The convective and impulsive masses are connected to the tank wall by corresponding equivalent spring having stiffness k_c and k_r, respectively. The damping constant of the convective and impulsive masses are cc and ci, respectively [13].

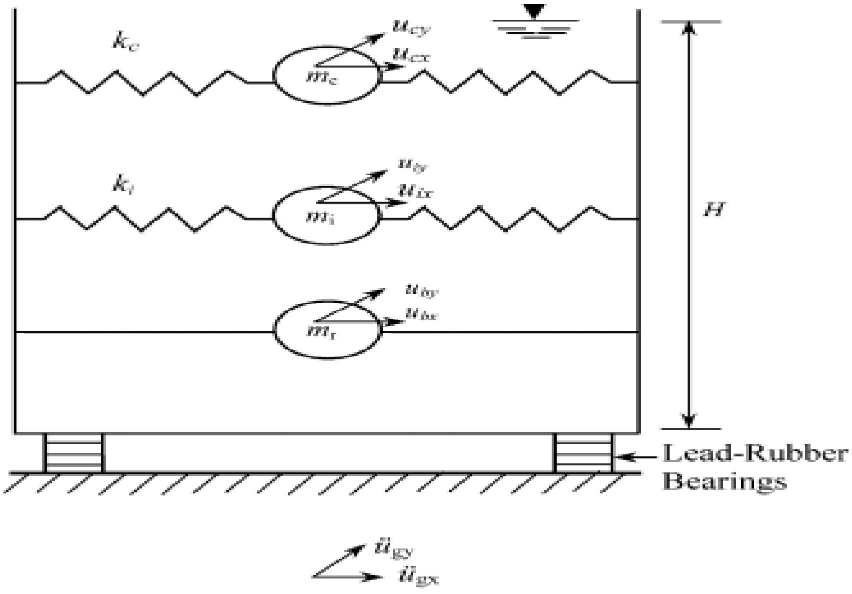


Fig. 1. Structural model of base-isolated liquid storage tank [13].

2.3 Force-deformation Behavior of Bearings

Fig. 2 shows the lead-rubber bearings considered which consist of alternative layers of rubber and steel plates with a central lead core. The bearing has isotropic property, which signifies the same dynamic characteristics in all directions. The bearing is modelled such that it has bi-linear force-deformation behavior in horizontal directions. The bearings are vertically stiff and have initial horizontal stiffness, k_b and viscous damping, c_b. The vertical stiffness are derived from steel plates while parallel layers of rubber bearings provide horizontal flexibility. The lead core yields relatively at very low shearing stress leading to dissipation of seismic energy and reduction of earthquake response (Robinson, 1982). where F_{bx} and F_{by} are the bearing forces in x-and y-directions, respectively; is an index which represents the ratio of post- to pre-yielding stiffness; kb is the pre-yielding stiffness of the bearing; x_b and y_b are the relative bearing displacements in x- and y-directions, respectively; F_y is the yield strength of bearings and the hysteretic components of displacement Z_x and Z_y are [13]. The seismic isolation subsystem is simulated by lead rubber bearing [LRB] that is a steel-reinforced material whose behavior is shown in Fig. 3.

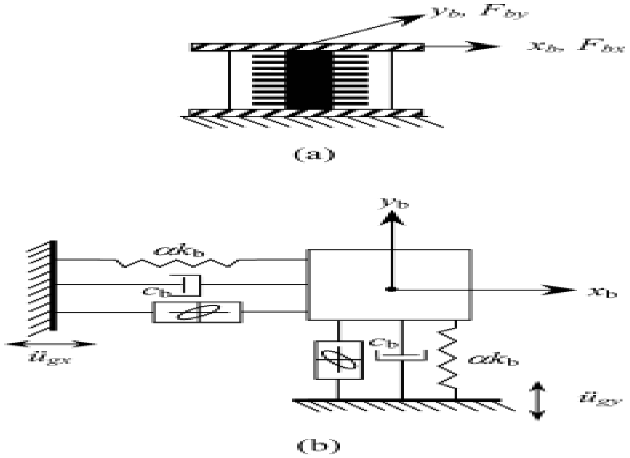


Fig. 2. (a) The isolation system and (b) Lead-rubber bearing [13].

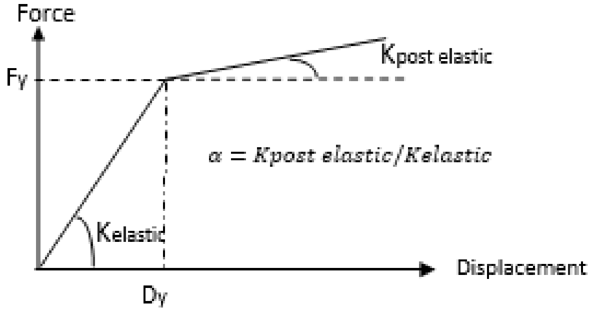


Fig. 3. Base-isolation stiffness modeling.

$$\begin{Bmatrix} F_{bx} \\ F_{by} \end{Bmatrix} = x \begin{bmatrix} k_b & 0 \\ 0 & k_b \end{bmatrix} \begin{Bmatrix} x_b \\ y_b \end{Bmatrix} + (1-x) \begin{bmatrix} F_y & 0 \\ 0 & F_y \end{bmatrix} \begin{Bmatrix} Z_x \\ Z_y \end{Bmatrix} (5)$$

2.4 Finite Element Formulation of Motion

The motion equations of isolated liquid storage tank subjected to seismic ground motion are expressed in the matrix as equation 6, [13]:

$$[m]\{\ddot{z}\} + [c]\{\dot{z}\} + [k]\{\dot{z}\} + \{F\} = -[m][r]\{\ddot{u}_g\} \qquad (6)$$

Where $\{z\} = \{x_c, x_i, x_b, y_c, y_i, y_b\}^T$ and $\{F\} = \{0, 0, (1-\alpha)F_y Z_x, 0, 0, (1-\alpha)F_y Z_y\}^T$ are the displacement and restoring force vectors, 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 ydirections, respectively; $x_i = u_{ix} - u_{bx}$ and $y_i = u_{iy} - u_{by}$ are the displacements of the impulsive mass relative to bearing displacements in x and y directions, respectively; [m], [c] and [k] are the mass, damping and stiffness matrix of the system, respectively; [r] is the influence coefficient matrix; and $\{\ddot{u}_g\} = \{\ddot{u}_{gx}, \ddot{u}_{gy}\}^T$ is the earthquake ground acceleration vector, the $\ddot{u}_{gx}$ and $\ddot{u}_{gy}$ are the earthquake accelerations in x-and y directions, respectively, $x_b = u_{bx} - u_{gx}$ and $y_b = u_{by} - u_{gy}$ are the displacements of the bearings relative to ground in xand y directions, respectively; The matrices [m], [c], [k]and[r] are expressed as relation 7.

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

$$[c] = diag[c_c, c_i, c_b, c_c, c_i, c_b] (7)$$

$$[k] = diag[k_c, k_i, xk_b, k_c, k_i, xk_b]$$

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

In equation 7, $M = m_c + m_i + m_r$ is the total effective mass of the tank [13].

3. Verification of the Finite Element Model

To perform the verification of the proposed, the results of water free surface displacement obtained from the numerical model, is compared with experimental results reported by Goudarzi [18]. The test tank was selected for verification process has rectangular shape with dimension of 0.96×0.4×1 m in length, breadth and height, respectively. The tank was fixed on a shaking table with dimension of 1×2 m in length, breadth, respectively, also the water height in the tank is considered 0.625 m. The water height in the tank is considered 0.625 m. The response of the rectangular tank was studied under the harmonic sinusoidal excitation. To prevent seismic damage of water tank natural frequency must be calculated, then the seismic frequency calculated via subjected to seismic wave should be difference of natural frequency. The test tank was excited with horizontal forced frequencies bigger than the first fundamental frequency of contained liquid which is obtained from the equation (8). The seismic wave motion is given by equation (9):

$$\omega_n{}^2 = \pi(2n-1)\left(\frac{g}{L}\right) tanh\left[(2n-1)\left(\frac{h}{L}\right)\right] \tag{8}$$

$$X_{(t)} = D\, sin(\omega t) \tag{9}$$

In above formula D is maximum horizontal amplitude and ω is horizontal forced frequencywhich were considered to 0.005 m and 6.221 HZ, n is number of oscillation modes and L is length of the tank. Natural frequency of first mode of experimental tank is equal to 0.887 HZ, that number of elements and the results of the finite element method are given in Table 1.

Table 1. Specifications of elements

Number of Elements			Number of fluid elements	Natural frequency (HZ)
In length	**In breadth**	**In height**		
20	8	12	1920	0.887

The Mann-Whitney analysis showed, there is no significant difference between the numerical and experimental data: (P-value =0. 619) > 0.05. Comparison between experimental and numerical results on verification processes are shown in Fig. 4.

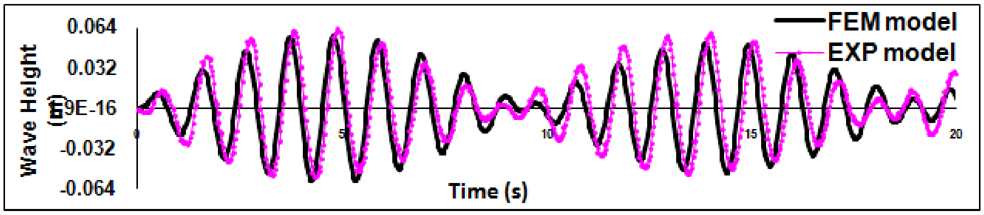


Fig. 4. Comparison between FEM results of sloshing wave height and experimental measurements (P-value=0. 619>0.05)

4 Selected Ground Motion Records

The three strong motion stations that recorded earthquake motions with peak ground accelerations larger than 0.21g were selected for dynamic analysis; these records are shown in Fig. 5. Due to the voluminous and time-consuming model analysis, the intensive volatility areas of the earthquake records are used for calculation.

Result of primary analysis shows the maximum of responses in water tank occurred in maximum acceleration in time history analysis, therefore, to decrease analysis time with a suitable scale factor the effective time of earthquake records has been applied in FEM analysis. For this purpose, the First, a static analysis was performed prior to the dynamic loading in these selected areas of earthquake records and parts of time-history record of the selected earthquakes must be considered carefully, therefore the effective time of Northridge earthquake record was selectedfrom 6.5 to 18.5 seconds, totally 12 seconds, the effective time of the San Fernando earthquake record was selected from 2 to 6seconds, totally 4 seconds and the effective time of the Kobe earthquake record was evaluated from 5 to 15seconds, totally 10 seconds were used.Studies have shown that these parts act a dominant role in the performed analyses.

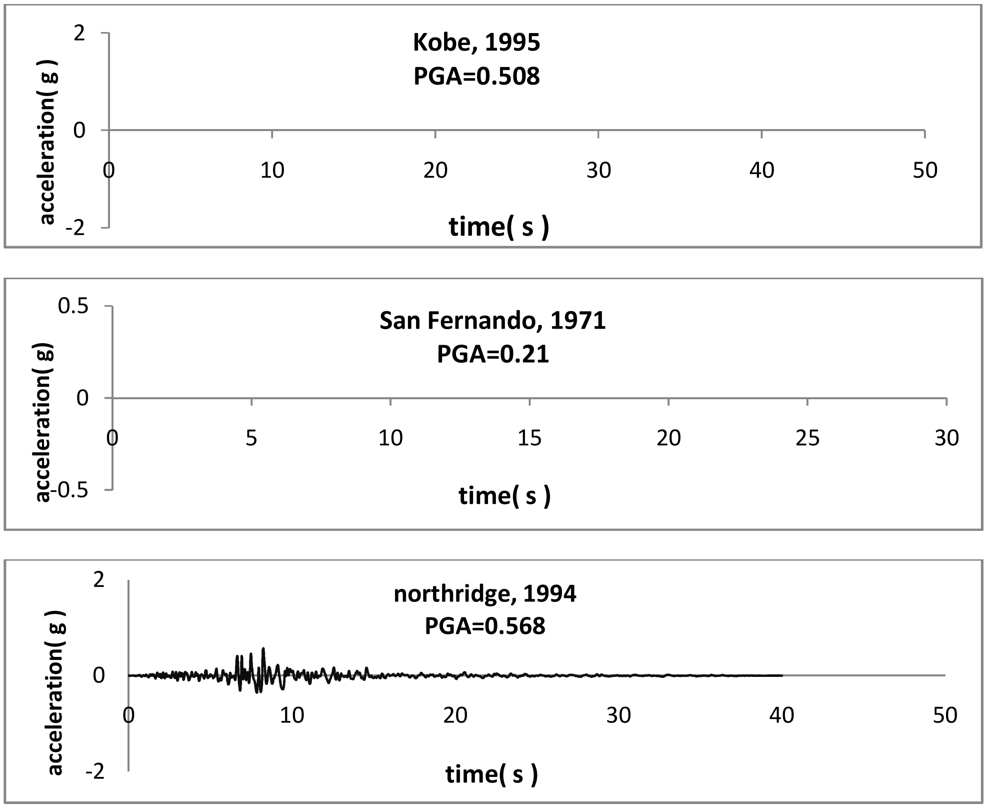


Fig. 5. Time history earthquake records under x and y directions [19].

5 Numerical Analysis

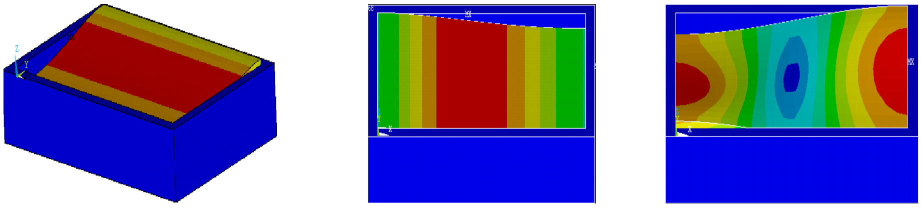
5.1 Modal analysis

Sloshing characteristics of a tank contain natural frequencies and mode shapes that are important parameters in the analysis. The determination of these parameters can be very useful in describing the tank's behavior. Modal analysis is used to determine these characters and original mode of structure in horizontal and vertical directions. Convective and impulsive modes are the most important vibration modes that have the maximum of mass contribution effects. This analysis could be a starting point for other analyses such as time history analysis.

The vibration modes of the rectangular liquid storage tanks are classified roughly into convective and impulsive. The lowest frequency of vibrating fluid and tank structure for without isolation tank with dimension of 23.5 ×15×4 m in length, breadth and height are inserted in Table 2, the water height in the tank was considered 3.16 m. Figs. 6 and 7 show the mode shapes in first three convective and impulsive modes of the fluid / tank system, respectively. That is implemented to simulate the behavior of the system in free vibration mode and to prevent creation of destructive phenomena such as resonance in the system.

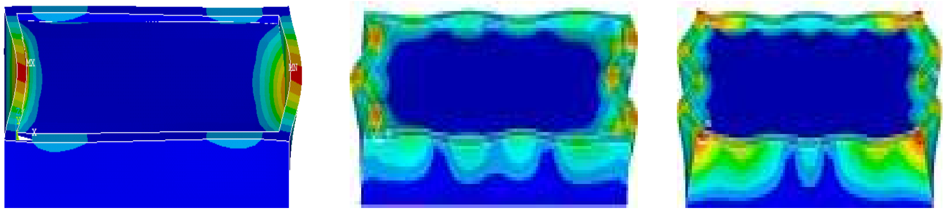
Table 2. The main frequency of the vibrating system (HZ)

Mode number	Fluid	Tank structure
1	0.119	32.18
2	0.184	33.65
3	0.201	37.97



a) First mode **b) Second mode** **c) Third mode**

Fig. 6. Displacement vector summation (X, Y, Z) for convective modes, a) first mode b) secondmode and c) Third mode



a) First mode **b) Second mode** **c) Third mode**

Fig. 7. Displacement vector summation (X, Y, Z) for impulsive modes, a) first mode b) second mode and c) Third mode

5.2 Time History Analysis

The numerical study was done with suitable finite element model with ability of modeling hybrid tank- fluid interaction, for this target ANSYS [20] software was selected. In thismodelFluid80, solid65 and combination40 elements are used for modelling of fluid, tank structure and damper respectively. These elements have 3 DOF at each node. For three-dimensional modeling, the tank is assumed to be a symmetric structure with four side flexible walls. The convective mass damping ratio is considered value about 0.005 (damping for water) and the impulsive mass damping is defined value about 0.02. Water Tank's Dimensions with 3.16 water Height were selected, based on Iranian code on analysis and design criteria of ground water tanks, (Code No. 123) [21].

In this section, the effects of passive base-isolation on the responses of liquid storage tanks are investigated. The non-linear dynamic analysis is performed to observe the seismic response of base-isolated liquid storage tanks. A finite element model of a three-dimensional rectangular tank is shown in Fig. 8.

The dimensions of this tank, Material properties of the considered system and base-isolation properties are inserted in Tables 3, 4, 5 and 6 respectively.

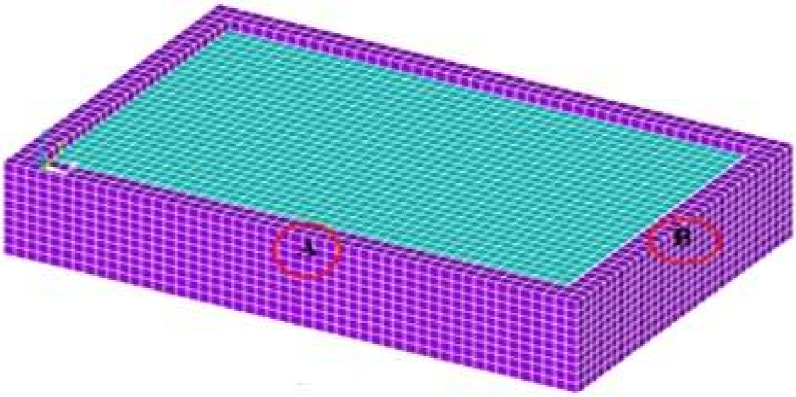


Fig. 8. Finite element model of a three-dimensional rectangular tank

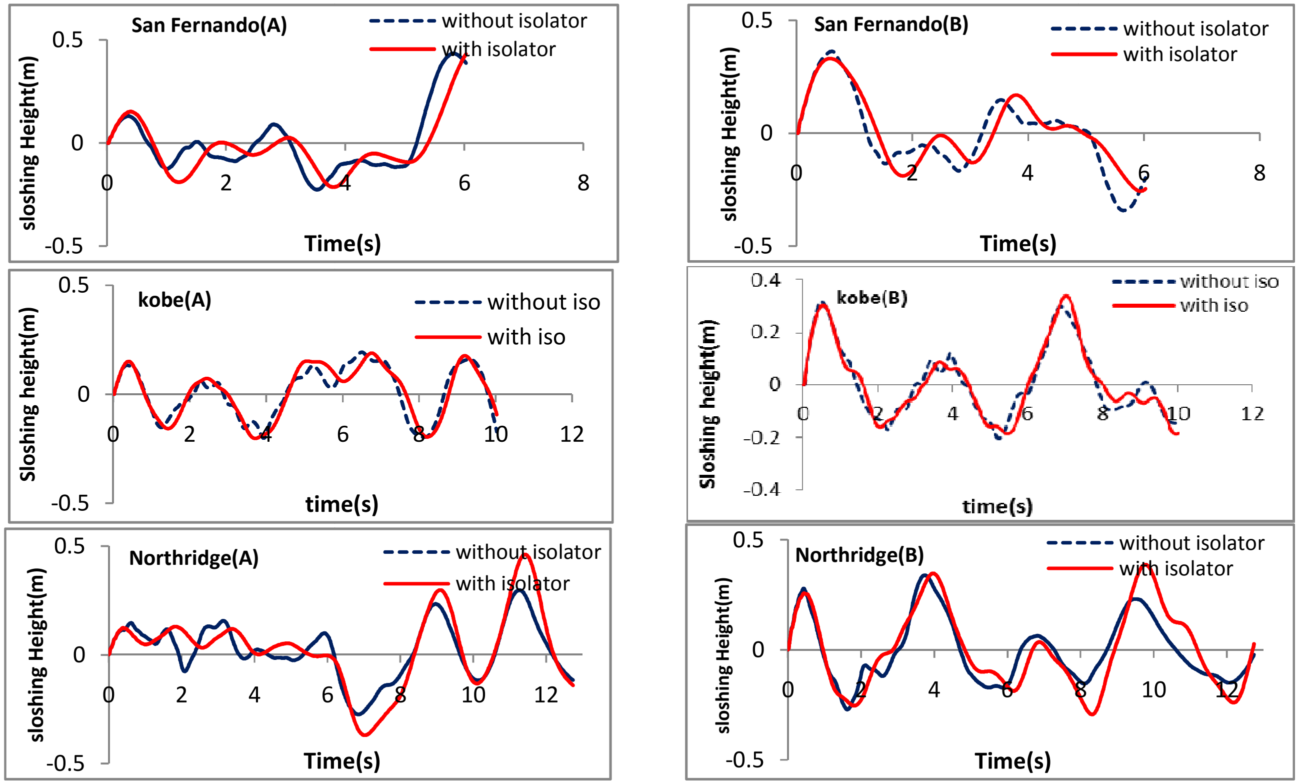
6 Results and Discussions

6.1 Sloshing

The results show, there is a smooth increase in the sloshing displacement with use of base isolation system compare with current non-isolated system. The sloshing results are presented in Fig. 9. The results of nonlinear dynamic analysis showed that maximum of fluid surface waves occurred in the vicinity of the tank wall. The changes of wave height on the water surface increases in isolated tank. The disadvantage of isolated tank is the undesirable effect of the increasing surface wave height. This is due to the high flexibility associated with the convective mass which brings its natural period closer to that of the isolated tank period.

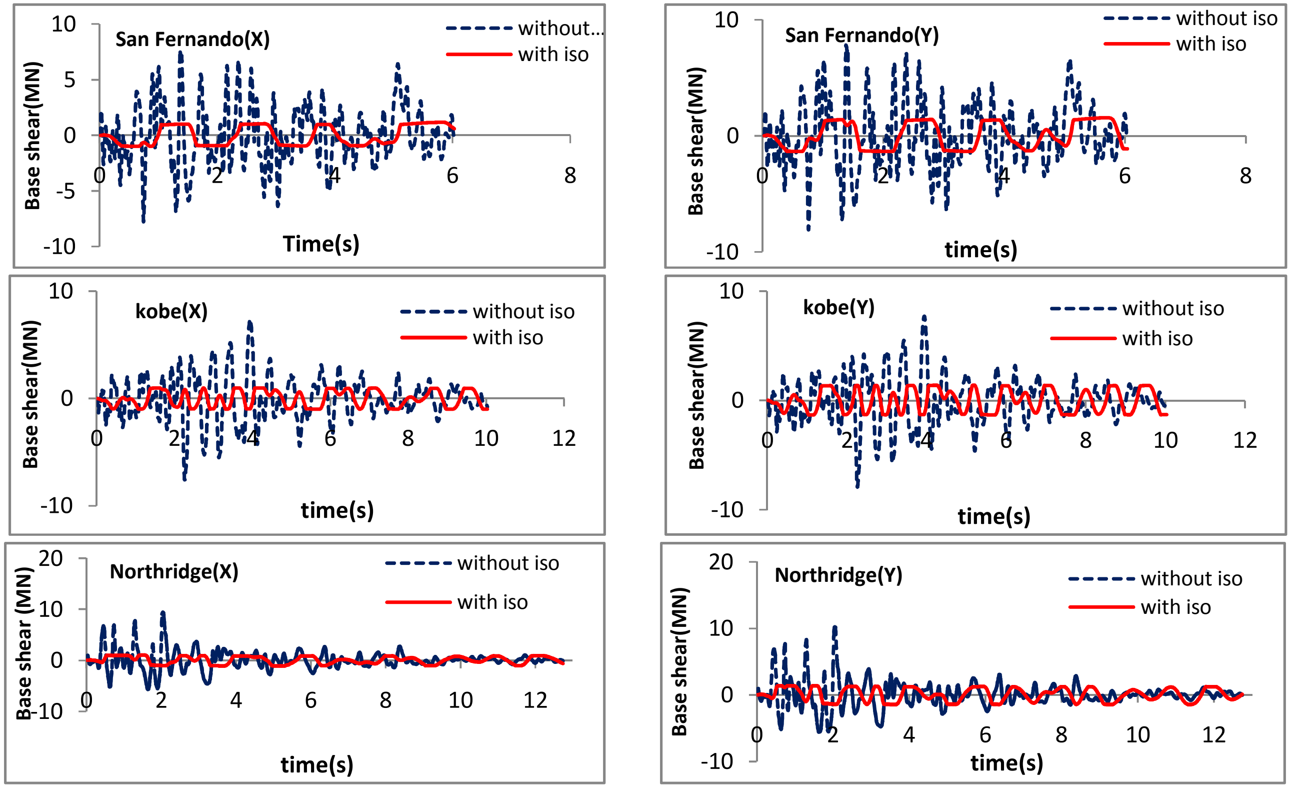
6.2 Base Shear

The results in Fig. 10 showed that the use of seismic base isolation, decreased approximately 70 to 80 percent of the base shear response. With the presence of base isolation, the first vibration mode period of the base isolation tank is much longer in comparison with the fixed one. In the same case, base shear values decrease in all of dynamic analyses that are considered as the advantage of the base isolation.



a) b)

Fig. 9. Time variation of sloshing quantities of isolated and non-isolated tank under san fernando, Kobe and Northridge earthquakes. a) A location b) B location



a) **b)**

Fig. 10. Time variation of base shear quantities of isolated and non-isolated tank under san fernando, Kobe and Northridge earthquakes. a) X direction b) Y direction

These results are in agreement with those observed by: Shrimali and Jangid [13,14], Shekari et al. [15], Soni et al. [22]. Seismic response of liquid storage concrete tanks isolated by the lead rubber bearing base isolator, LRB, is investigated. The calculated sloshing response or the variation of liquid level and base shear response in the X and Y direction during the selected earthquakes are shown in Figs. 9 and 10. The properties of the isolated system (such as stiffness, damping and friction) were not kept the same in both x-and y-directions of the system. It is observed that base shear is significantly reduced in comparison to those non-isolated system in both directions, but without significantly affecting the wave height on the water surface.

Table 3. Properties of tank and liquid domain

Mass density of the concrete	Young's modulus of the concrete	Poisson's ratio of the concrete	Mass density of the liquid	Bulk modulus of the liquid
$2300\,\mathrm{kg/m^3}$	26.44 GPa	0.17	$1000\ \mathrm{kg/m^3}$	2.1 GPa

Table 4. Dimensions of tank and liquid domain

Tank length	Tank width	Tank height	Water height	Tank thickness
23.5m	15m	4m	3.16m	0.5m

Table 5. Properties of base-isolation (X)

Fy	kelastic	Kpost elastic	Dy	Mass
0.9MN	79.4 MN/m	1MN/m	0.012m	1N.s^2/m

Table 6. Properties of base-isolation (Y)

Fy	kelastic	Kpost elastic	Dy	Mass
1.3MN	109.2MN/m	1.4MN/m	0.012m	1N.s^2/m

7 Conclusion

Some of the past and present research studies on seismic response analysis for liquid storage tanks were reviewed. In addition, new dynamic analysis for comparison of seismic response of isolated and non-isolated liquid storage tanks under two horizontal components of real earthquake ground motions was performed. The dynamic analysis to evaluate seismic response sloshing and base shear was proposed and validated by the experimental results. The conclusions obtained are summarized as follows:

1. A verification of FEM was performed, the experimental and numerical values were compared with statistical analysis based on Mann-Whitney rules showed there is no significant difference between the numerical and experimental data: (P-value=0.619) > 0.05.
2. The sloshing displacement in dynamic analyses is presented in the Fig. 7. The results of nonlinear time history analysis of the maximum fluid surface waves that occur in the vicinity of the tank wall are shown. The sloshing displacement is not much affected by

the isolation approaches. The sloshing frequency is influenced by the material properties of the tank wall, and they are the same for all of the tank models.

3. It can be observed that there are considerable differences in the base shear responses obtained of the two different modeling of base isolation systems under X and Y directions in comparison with non-isolation system, in all selected seismic records. It is noticed that due to the base-isolation system the base shear is reduced significantly. The reduction in base shear leads to a reduction in the tank wall thickness and hence more economic design.

Competing Interests

Authors have declared that no competing interests exist.

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