Earthquakes and Structures, Vol. 2, No. 4 (2011) 397-412

DOI: http://dx.doi.org/10.12989/eas.2011.2.4.397

Seismic analysis and modeling of isolated elevated liquid storage tanks

Ayman A. Seleemah* and Mohamed El-Sharkawy

Structural Engineering Department, Faculty of Engineering, Tanta University, Egypt

(Received January 20, 2011, Revised May 11, 2011, Accepted May 17, 2011)

Abstract. In this paper, the seismic response of elevated broad and slender liquid storage tanks isolated by elastomeric or sliding bearings was investigated. The accuracy of predictions of SAP2000 vs. 3D-BASIS-ME programs was examined. A comparative study of the performance of base isolated tanks when isolation bearings are placed at the top or at the bottom of the supporting tower structure was conducted. It was found that base isolation is quite effective in reducing the earthquake response of elevated liquid storage tanks in which high reductions of base shear and shaft displacement were achieved. Modeling the isolated tanks in SAP2000 was very successful in producing results that are nearly identical to those of program 3D-BASIS-ME. Placing the isolators at the top of the shaft in elevated tanks proved to be much better than placing them at the bottom.

Keywords: elevated tanks; seismic isolation; liquid storage; modeling; 3D-BASIS-ME; SAP2000.

1. Introduction

Seismic isolation technology has found an increasing number of applications over the last decade and particularly over the last few years. The increase in the use of this technology may be attributed to the development of analysis and design guidelines and specifications and the availability of computer programs for dynamic analysis. The need for a dynamic analysis computer program dedicated to seismically isolated buildings was fulfilled in part with the release of 3D-BASIS-ME, Tsopelas *et al*. (1994).

Program SAP2000, CSI (2005) is a version of the popular SAP series for commercial structural analysis programs. SAP2000 has the feature of nonlinear dynamic analysis with elements for seismic isolation and energy dissipation hardware. The program has already been used for the analysis of a number of structures with seismic isolation or energy dissipation systems, and has the potential for widespread use.

Neither 3D-BASIS-ME nor SAP2000 have the capability of explicitly modeling the dynamic behavior of a liquid storage tank, that is, to directly model fluid-structure interaction. However, both programs are capable of analyzing mechanical models of the liquid-tank system such as that described by Haroun and Housner (1981). In this approach, mathematical analysis is employed in order to arrive at a representation of the system consisting of an assemblage of oscillators, each one

* Corresponding author, Associate Professor, E-mail: seleemah55@yahoo.com

of which simulates a specific effect, such as sloshing of the liquid, deformation of the liquid-tank system and impulsive response. The calculated response of these oscillators is then used to evaluate important response quantities for design, such as base shear and bending moment induced by the hydrodynamic wall pressure, and vertical displacement of the liquid.

Behavior of isolated tanks has received considerable attention by researchers. For example, Shenton and Hampton (1999) studied the seismic response of isolated elevated water tanks by developing a discrete three-degree-of-freedom model. Shrimali (2002) investigated the seismic response of elevated liquid storage steel tanks isolated by non-linear elastomeric bearings considering the influence of various isolation parameters. Kim *et al*. (2002) presented a three-dimensional soil–structure–liquid interaction problem in order to analyze the dynamic behavior of base-isolated liquid storage tanks subjected to seismic ground motion. Shrimali and Jangid (2003) studied the comparative performance of elevated liquid storage steel tanks, isolated by linear elastomeric bearings, by placing the base isolation system at top and bottom of the supporting tower. Cho *et al*. (2004) examined the seismic response analysis of a base- isolated liquid storage tank on a half-space using a coupling method that combines the finite elements and boundary elements. Shrimali (2005) studied the comparative performance of isolated elevated liquid storage steel tanks with linear elastomeric bearings (LRB) and sliding bearings (FPS). Livaoglu and Dogangun (2007) investigated the effects of foundation embedment on the seismic behavior of fluid-elevated tank-foundation–soil system with a structural frame supporting the fluid containing tank. Shrimali (2007) studied the seismic response of elevated cylindrical liquid storage steel tanks isolated by resilient-friction base isolator (R-FBI). Maleki and Ziyaeifar (2007) studied the effect of baffles in reducing earthquake responses of seismically isolated cylindrical liquid storage tanks. Almazán *et al*. (2007) investigated the dynamic response of thin-walled legged wine tanks with seismic isolation. Hino *et al*. (2008) proposed a new recursive analysis method of axial deformation of rubber bearings taking into account their nonlinear tensile behavior. It was shown that the relaxation of the constraint on the ultimate state of the tensile stress of rubber bearings increases the limiting aspect ratio. Shekari *et al*. (2009) studied the effects of base-isolation on the seismic response of cylindrical vertical flexible liquid storage tanks subjected to horizontal seismic ground motions. Abalı and Uckan (2010) focused on earthquake performances of both broad and slender tanks base isolated by FPS bearings. Goudarzi and Alimohammadi (2010) studied both fixed base and isolated vertical, cylindrical, liquid storage tanks with different aspect ratios using lead rubber bearings isolators. A finite element model was constructed taking fluid-structure interaction effects into consideration.

In this paper, the seismic response of elevated liquid storage tanks isolated by elastomeric or sliding bearings is investigated. The specific objectives of this paper are: (i) to investigate the effectiveness of seismic isolation of elevated liquid storage tanks by comparing the response of the tank with and without isolation; (ii) to compare the peak response of liquid storage tanks isolated by elastomeric or sliding bearings to determine the best type of isolation system for elevated tanks; (iii) to conduct a comparative study of broad and slender elevated tanks; (iv) to help wide spreading of the seismic isolation technology for tanks among engineers by using SAP2000 as a common, user friendly program for designers for modeling elevated tanks involving seismic isolation system and compare the obtained results with those obtained utilizing program 3D-BASIS-ME; (v) to conduct a three dimensional analysis of the tank under real earthquakes (with three components) and study the overturning moment effects that may cause bearing uplift (i.e. make tension force in the bearing); and (vi) to study comparative performance of base isolated tanks when isolation bearings are placed at top or at bottom of the supporting tower structure and determine the optimum location of seismic isolation in elevated tanks.

The present study includes two types of elastomeric bearings. These are the lead rubber bearing system, often called N-Z system; and high damping rubber bearing system, (HDRB system). The study also includes one type of sliding bearings, friction pendulum system (FPS). Moreover, three real earthquake motions were used as the exciting motions. These are El-Centro (1940), Northridge (1994), and Kobe (1995) earthquakes.

For complete investigation of the seismic behavior of liquid storage elevated tanks, key response parameters will be compared. The main response quantities of interest are the base shear (Vs), the convective displacement (Xc), the top drift of the shaft support; namely shaft displacement (Xs) and the isolation system displacement; namely base displacement (Xb). The response of the isolated tank is compared with the corresponding response of the tank without isolation system. Also, the response obtained utilizing the three isolation systems, namely N-Z, HDRB and FPS systems are compared.

2. Model of seismic isolated elevated liquid storage tank

Cylindrical liquid storage concrete tanks with cylindrical shaft support were selected for the current study. The contained liquid is considered as incompressible, inviscous and has irrotational flow. During the base excitation and since the tank wall is rigid, no impulsive motion takes place. The entire tank liquid mass vibrates in two distinct patterns such as sloshing or convective mass (i.e. top liquid mass which changes the free liquid surface) and rigid mass (i.e. the lower liquid mass which rigidly moves with the tank wall). The response can be predicted by considering first sloshing mode only. Therefore, the continuous liquid is modeled as two lumped masses with rigid tank, Newmark and Rosenblueth (1971). This mechanical model is in agreement with the mechanical model of Malhotra *et al*. (2000), that was build to model both flexible and rigid tanks.

3. Mechanical model of fluid tank

Fluid is replaced by a rigid mass m_0 that is rigidly attached to the tank wall and a convective mass m_c that is attached to the tank wall by a linear spring of stiffness k_c (see Fig. 1). The equations for the fluid masses and convective spring stiffness for a cylindrical tank are given by Newmark and Rosenblueth (1971) as following

$$m_c = 0.71m\frac{\tanh(1.8H/R)}{1.8H/R} \tag{1}$$

$$m_0 = m\frac{\tanh(1.7R/H)}{1.7R/H} \tag{2}$$

$$K_c = 4.75\frac{m_c^2}{m}\frac{gH}{R^2} \tag{3}$$

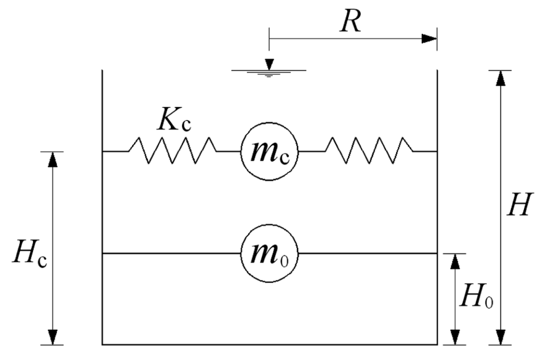

Fig. 1 Mechanical analog proposed by Newmark and Rosenblueth (1971) for rigid cylindrical tank wall

Where m is the total mass of the fluid; H is the height of the fluid, R is the radius of the tank, and g is the gravity acceleration. The rigid and convective masses are located at distances H_0 and H_c, respectively, from the bottom of the tank; the heights are given by

$$H_0 = \frac{3}{8}H\left\{1 + \frac{4}{3}\left(\frac{m}{m_0} - 1\right)\right\} \tag{4}$$

$$H_c = H\left\{1 - 0.21\frac{m}{m_c}\left(\frac{R}{H}\right)^2 + 1.1\frac{R}{H}\sqrt{0.15\left(\frac{R.m}{H.m_c}\right)^2 - 1}\right\} \tag{5}$$

4. Modeling liquid storage tanks using 3D-BASIS-ME

Program 3D-BASIS-ME was utilized to model the tanks in this study. 3D-BASIS-ME is a special purpose computer program designed to analyze structures with nonlinear base isolation devices subjected to seismic motion. The program was developed to enable analysis of various isolation devices such as elastomeric bearings with low and high damping characteristics, sliding bearings, and spherical sliding systems such as FPS bearings, under realistic seismic motion. The program is capable of analyzing single as well as multiple superstructures with a single isolation basemat which makes it suitable for the dynamic analysis of isolated liquid storage tanks in which the liquid-tank system is modeled by two-degree-of-freedom systems, representing the impulsive and convective effects.

4.1 Specific features of 3D-BASIS-ME

Program 3D-BASIS-ME has the feature of detailed modeling of the isolation system with spatial distribution of isolation elements and explicit or implicit nonlinear force-displacement characteristics of individual isolation devices. The library of isolation elements include elastomeric and sliding bearings with bi-directional interaction effects.

The program also has the option of including overturning moment effects through the use of an externally supplied function, and of vertical ground acceleration. Since vertical degrees-of-freedom are excluded in the program, the specified vertical ground acceleration is used to directly modify the instantaneous vertical load on the bearings. However, Scheller and Constantinou (1999) suggested to use a modified vertical acceleration history, which takes into account the vertical flexibility of the tank, that is calculated by an independent analysis of the system in the vertical direction.

4.2 The numerical model

The geometries of the studied broad (H/R=0.72) and slender (H/R=1.64) elevated tanks along with their mechanical models are shown in Fig. 2. The weights of water (for full tank), tank body, shaft support, basemat, and total isolated weight for both broad and slender tanks are 2210, 1835, 2422, 1108, and 7575 Kips, respectively. The oscillators shown in the figure are represented as a shear-type structure with two stories connected to the center of mass of the basemat which is located at its geometric center. The top story presents the convective mass (m_c) with damping ratio $\zeta = 0.005$ (damping for water); the height of this story equal to the effective height for the convective mass from the mechanical model (Hc) and its stiffness equal to the effective stiffness for the convective mass (Kc). The bottom story presents the summation of the rigid mass (m_0), the mass of the tank container and half of the mass of the shaft support, its height equals to the height of the shaft support (Hs), its stiffness equals to the stiffness of the shaft support and its damping $\zeta = 0.05$ (typical damping for concrete structures). It should be noted that the effective height for the rigid mass (H_0) is neglected, Shenton and Hampton (1999), and the second half of the mass of the shaft support is rigidly attached to the concrete basemat, rasing its weight.

4.3 Results

Time variations of various response quantities of broad and slender elevated tanks under Kobe excitation are illustrated in Fig. 3. The responses are shown for both isolated and non-isolated conditions. Moreover, base shear over weight-displacement loops of broad and slender elevated tanks with N-Z, HDRB and FPS systems under Elcentro earthquake are illustrated in Fig. 4. Table 1 summarizes the peak responses of isolated and non-isolated, broad and slender tanks under the three earthquake motions considered.

4.3.1 Response of the tank with and without isolation

From the time histories shown in Fig. 3, it is observed that the base shear over weight (Vs/W) and shaft displacement (Xs) of the isolated tanks for all isolation systems are significantly reduced in comparison to that without isolation system. Such observation can be confirmed from Table 1 in which reductions ranged between 60% to 80% for the base shear, and 62% to 83% for the shaft displacement, respectively. This indicates that base isolation is quite effective in protecting the tanks against earthquakes. The reduction in base shear leads to reduction in the shaft thickness and reinforcement and hence less overall weight and more economic design. It is also observed that, as a result of isolation, there is moderate increase in the convective displacement (long period mode). The reason for that is attributed to the elongation of the natural period of the isolated tank. Such increase in the convective displacement was also observed by Shrimali (2005) and Goudarzi and Alimohammadi (2010). However, such behavior has no practical consequences except for the need to increase the clear height above the liquid surface.

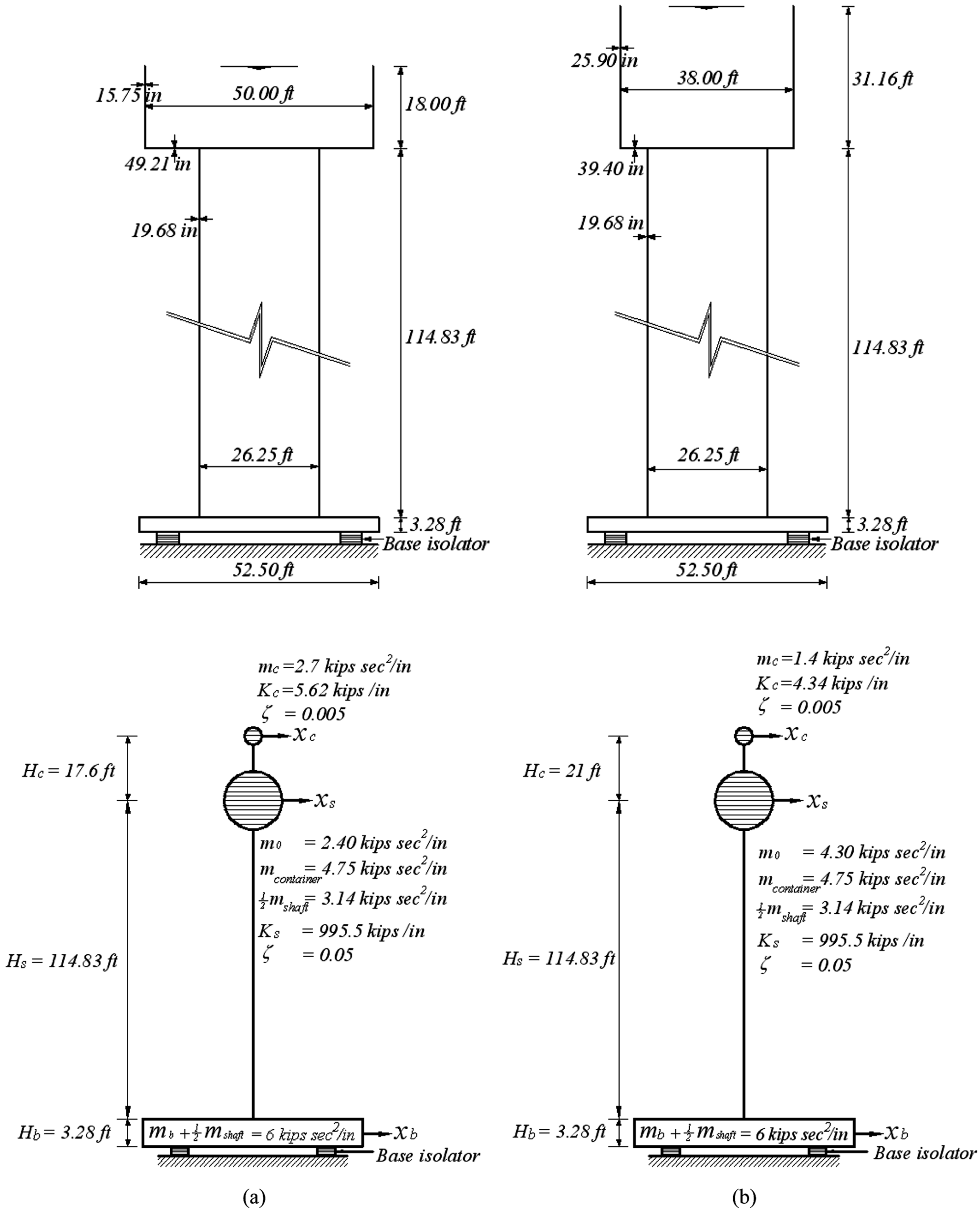

Fig. 2 Geometry and models of elevated water tanks: (a) Broad tank and (b) Slender tank

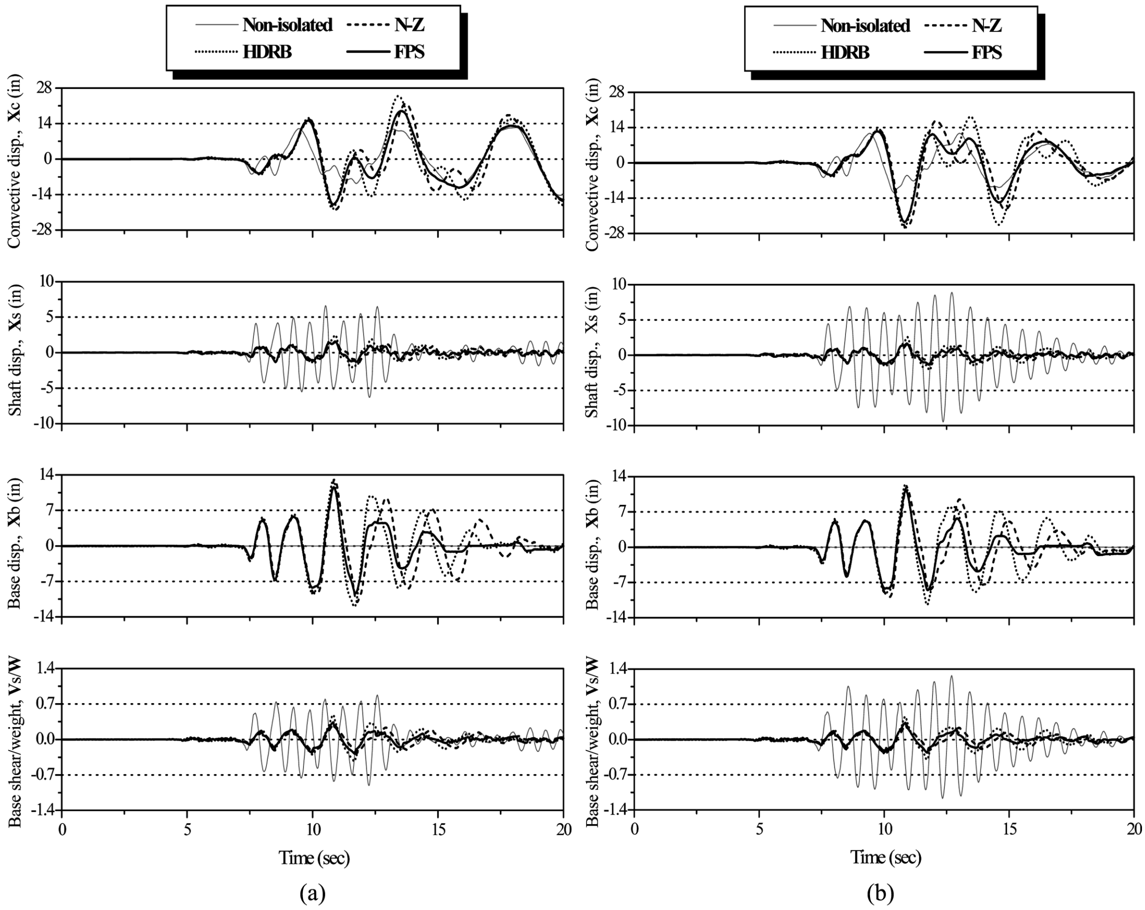

Fig. 3 Time variation of response quantities of elevated tanks under Kobe earthquake: (a) Broad tank and (b) Slender tank

4.3.2 Response of the tank with elastomeric or sliding bearings

Comparison of the loops shown in Fig. 4 indicates higher capability of the sliding FPS system to control the base displacement. This holds true for both broad and slender tanks and for all other earthquake excitations (Refer to Table 1). The base shear for the FPS and N-Z systems are generally comparable and less than those associated with HDRB system. Judgement on the overall results indicates that the FPS system is more effective to reduce both the base shear and displacement responses in comparison with N-Z or HDRB systems.

4.3.3 Response of broad and slender tanks

From the peak response quantities of broad and slender tanks shown in Table 1, it is observed that, the average reduction percentage in the base shear are 66 % and 70 % for broad and slender tanks, respectively. The reduction of base shear for slender tank is slightly greater than the broad tank, implying that the seismic isolation is a little more effective for slender tanks. This observation is compatible (to a less extent) with that reported by Sherimali (2002). Moreover it is observed that the average reductions in the shaft displacement are comparable for broad and slender tanks, (76% and 77 %), respectively.

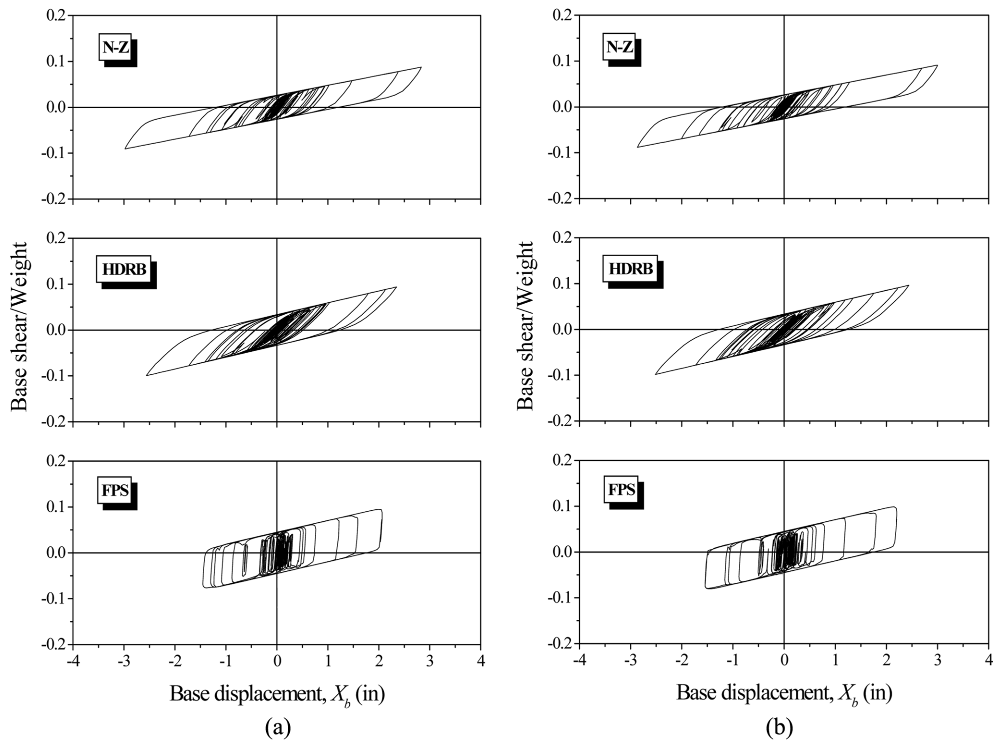

Fig. 4 Base shear/weight-displacement loops of elevated tank with N-Z, HDRB and FPS systems under El-Centro earthquake: (a) Broad tank and (b) Slender tank

Table 1 Peak responses of broad and slender elevated tanks

Earthquake	Type of tank	Non-isolated tank			Isolated tank											
					N-Z system				HDRB system				FPS system			
		Xc (in)	Xs (in)	Vs/W	Xc (in)	Xs (in)	Xb (in)	Vs/W	Xc (in)	Xs (in)	Xb (in)	Vs/W	Xc (in)	Xs (in)	Xb (in)	Vs/W
El-Centro N00E	Broad	6.95	2.96	0.387	8.91	0.51	2.98	0.090	8.48	0.59	2.56	0.099	8.12	0.56	2.07	0.095
	Slender	8.58	2.88	0.419	12.83	0.55	3.00	0.091	11.56	0.63	2.52	0.098	10.85	0.63	2.20	0.098
Northridge N90S	Broad	16.75	4.78	0.585	27.27	1.00	7.52	0.189	26.79	1.14	7.38	0.224	24.75	1.10	6.00	0.196
	Slender	16.17	4.31	0.570	32.73	1.19	8.51	0.210	28.81	1.23	7.85	0.236	25.77	1.14	6.35	0.200
Kobe N00S	Broad	14.29	6.64	0.911	21.97	1.55	13.14	0.310	24.84	2.49	13.07	0.486	18.98	1.58	11.60	0.340
	Slender	11.74	9.49	1.270	25.67	1.63	11.94	0.285	25.74	2.57	12.48	0.456	23.52	1.64	11.28	0.332

5. Modeling liquid storage tanks using SAP2000

Unlike program 3D-BASIS-ME, program SAP2000 has a three-dimensional formulation which allows for direct consideration of the vertical ground acceleration and overturning moment effects. These overturning moments can cause vertical tension forces on the isolators. It is known that most available seismic isolation systems cannot carry tension forces or can carry limited levels of tension forces. Of course, there exist seismic isolation systems that are able to carry high tension forces. But these systems are expensive and have been used in a limited number of projects. Program SAP2000 will be utilized to study the developed axial force in the isolators. Moreover, the program will also be used to investigate the optimum location of isolators in elevated tanks.

5.1 Specific features of SAP2000

SAP2000 is a user friendly software that has some elements capable of modeling seismic isolators. Among these are the nonlinear link and support elements. The types of nonlinear behavior that can be modeled with these elements include uniaxial plasticity (Wen model); multi-linear uniaxial plasticity with several types of hysteretic behavior such as (kinematic, Takeda, and pivot); biaxial plasticity base isolator; and friction pendulum base isolator. Following is a description of two of these elements.

Hysteretic (rubber) isolator element

This is a biaxial hysteretic isolator that has coupled plasticity properties for the two shear deformations, and linear effective stiffness properties for the remaining four deformations. The plasticity model is based on Wen model for hysteretic behavior.

Friction-pendulum isolator property

This is a biaxial friction pendulum isolator that has coupled friction properties for the two shear deformations, post-slip stiffness in the shear directions due the pendulum radii of the slipping surfaces, gap behavior in the axial direction, and linear effective stiffness properties for the three moment deformations. The friction forces and pendulum forces are directly proportional to the compressive axial force in the element. The element cannot carry axial tension.

5.2 The numerical model

Program SAP2000 have been utilized to model the tank as illustrated in Figs. 5 and 6. The model consists of the following elements:

- Shell elements to represent the tank body, shaft support and basemat. The thicknesses of the shell elements are the same as the actual geometry of the tank.
- The convective mass was presented by a lumped mass, m_c = 2.7 kips sec^2/in at a joint located at the center of the tank with a height Hc = 17.6 ft.
- Link element to represent the stiffness in the horizontal direction of the convective mass by linear properties Kc = 5.62 kips/in and damping ζ = 0.005 (fluid damping).
- The rigid mass was presented by a lumped mass, m_0 = 2.4 kips sec^2/in at the center joint of the base of the tank (i.e. at the top of the shaft support).
- Horizontal rigid links at the base of the tank to avoid local deformations and local modes, Dutta *et al*. (2003).

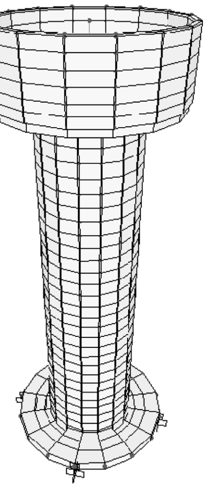

Fig. 5 Three dimensional model of the tank in SAP2000 program

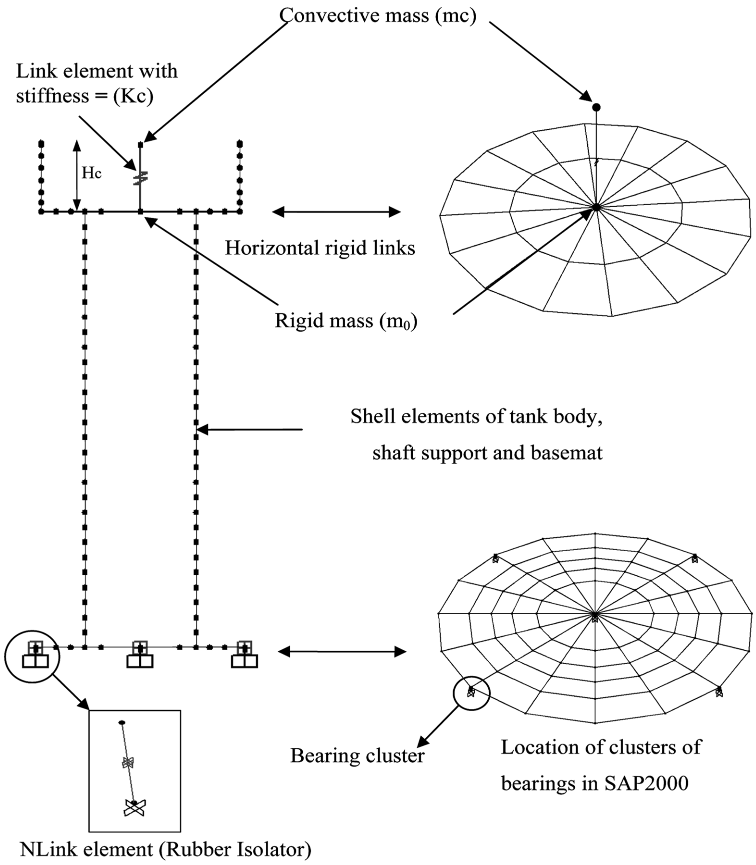

Fig. 6 Idealized model in SAP2000 showing shell elements of tank body, shaft support and basemat, convective mass, rigid mass, horizontal rigid links, linear link element with stiffness (*Kc*) and nonlinear link element (Rubber Isolator)

• The isolation bearings (N-Z system), which have bilinear hysteretic behavior, were modeled with NLink element. This element has coupled bilinear hysteretic behavior for the two shear deformations, whereas the remaining four degrees of freedom (axial deformation and three rotations) are linear. The isolators are represented by five clusters of bearings as shown in Fig. 6. Among the parameters describing this model, the linear vertical effective stiffness 10000 kips/in for one cluster (stiffness in direction u_1). The properties for the two nonlinear degrees of freedom (direction u_2 and u_3) for one cluster are the nonlinear elastic stiffness K_e = 212.29 kips/in, the yield strength F_y = 46.91 kips and the post yield stiffness ratio α =0.154.

5.3 Results

The functions calculated from SAP2000 are the time-history for convective displacement Xc, that is calculated at the joint of the convective mass; the time-history for shaft displacement Xs, that is calculated at the top of the shaft support; the time-history for base displacement Xb, that is calculated at the central cluster of the base; and time history for the total base shear at the base of the tank.

5.4 Comparison of the results obtained by using SAP2000 and 3D-BASIS-ME

In order to compare the results of both programs, the available degrees of freedom of the model

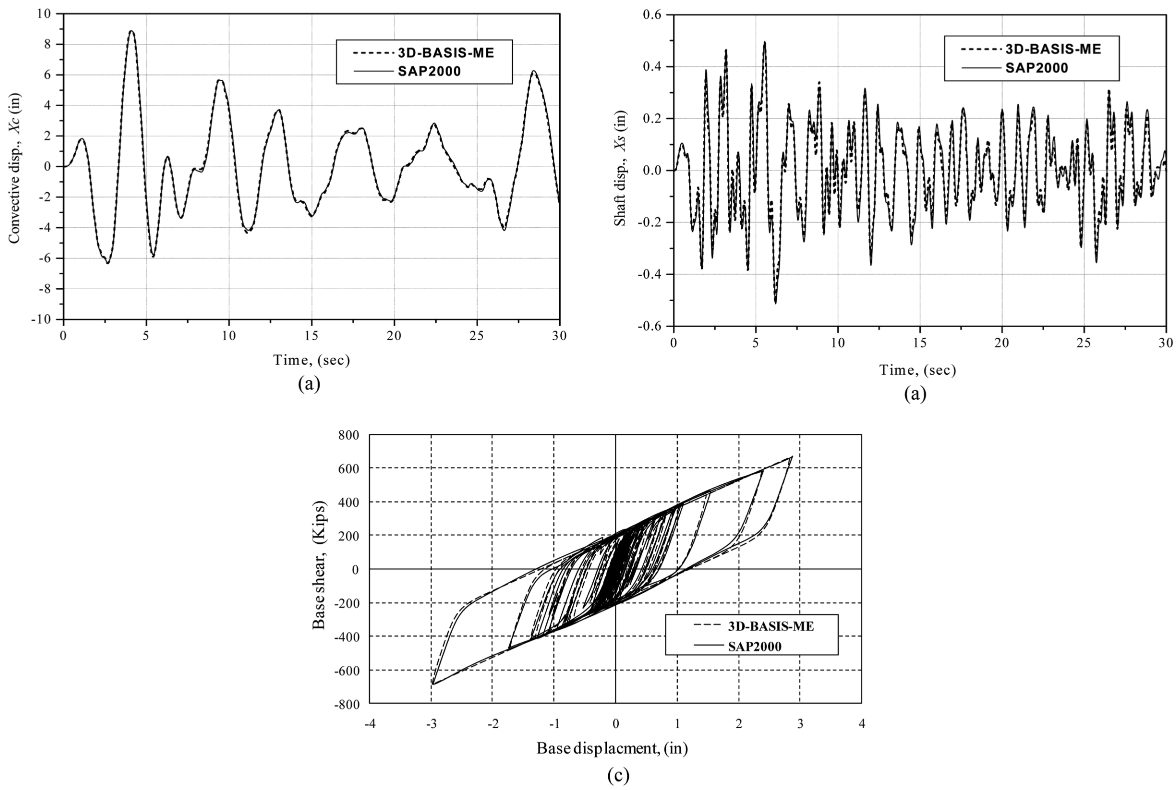

Fig. 7 Comparison of time history responses of 3D-BASIS-ME and SAP2000: (a) convective displacement, (b) shaft displacement and (c) base shear-displacement loops

in SAP2000 have been reduced to u_x only, while u_y and u_z were restrained as modeled by 3D-BASIS-ME. Fig. 7 shows comparison of calculated time histories of convective displacement, shaft displacement, and base shear-displacement loops obtained from 3D-BASIS-ME and SAP2000 programs. The comparison is very satisfactory indicating that, in general, modeling the isolated tanks in SAP2000 is very successful in producing results that are nearly identical to those of program 3D-BASIS-ME. Such good agreement of the results helps wide spreading of the seismic isolation technology among practicing engineers using SAP2000 as a common and user friendly software.

6. Optimum location of seismic isolation in elevated tanks

To find out the optimum location of seismic isolation in elevated tanks, two possible alternatives were studied. These are: (1) when the isolation system is located at the bottom of the shaft support; and (2) when the isolation system is inserted between the top of the shaft and the bottom of the tank container. The two solutions are illustrated in Fig. 8. In order to make the comparison realistic, all constraints that were applied for comparison between SAP2000 and 3D-BASIS-ME were released. That is, all degrees of freedom were released to allow for overturning effect. It should be mentioned that, for the second case where the isolators are located at the top of the shaft, the isolators were redesigned for the actual isolated weight that does not include the shaft or the base weights. Both solutions were analyzed and the comparison of the results will help in deciding the optimum location of the isolators. Comparison of the behavior of both cases was conducted in terms of the vertical force developed in the isolators and the total base shear. The left cluster was selected for the comparison of the vertical force in the isolators (see Fig. 8). The results are shown in Figs. 9 and 10.

6.1 The numerical model of the tank with isolation at top

The model with isolation system at top will have fixed base as shown in Fig. 8(b). Two layers of horizontal rigid links are placed at the top of the shaft support and at the bottom of the tank container. The vertical distance between these two layers equals to the height of the bearings such that to allow for the bearings to be placed between the two layers. The N-Z bearings were represented again by five equal clusters. The properties for the two nonlinear degrees of freedom (direction u_2 and u_3) for one cluster are the nonlinear elastic stiffness K_e = 113.49 kips/in, the yield strength F_y = 25.08 kips and the post yield stiffness ratio α =0.154.

6.2 Comparison of the response of the tank with isolators placed at top and at bottom

Fig. 9 presents a comparison of the time histories of vertical force in the left cluster of isolation system when it is placed at bottom or at top of the shaft. It is clear that the vertical force in the case of isolation at top is very small compared to that when the isolation system is placed at bottom. Fig. 10 presents a comparison of the time histories of base shear in the two alternatives. When the isolation system was placed at top, the base shear increased about 50% over that when the isolation system was placed at bottom. This is expected because the shaft and basemat are not isolated in this particular solution. However, this base shear is still less than 50% of that occurring in the case of

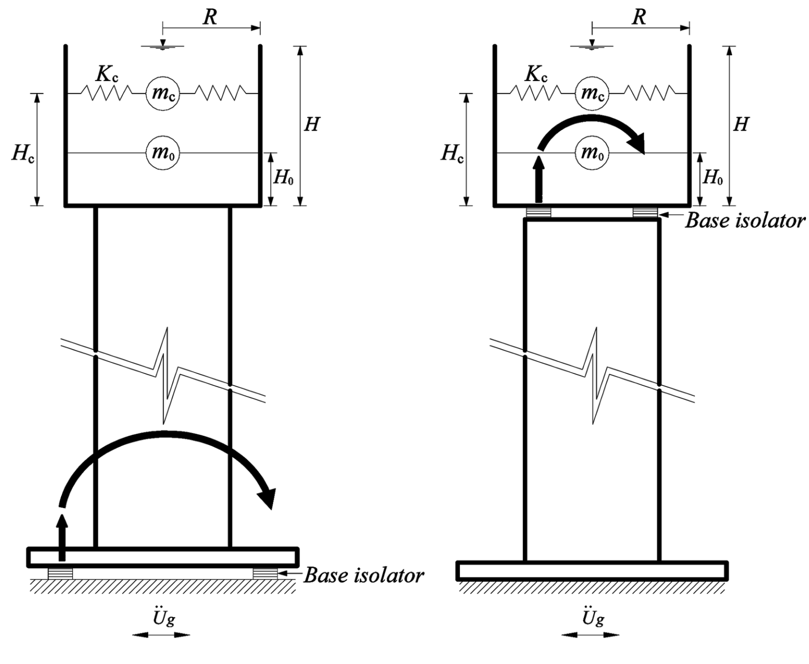

Fig. 8 Mechanical models of isolated elevated water tanks: (a) seismic isolation at bottom and (b) seismic isolation at top

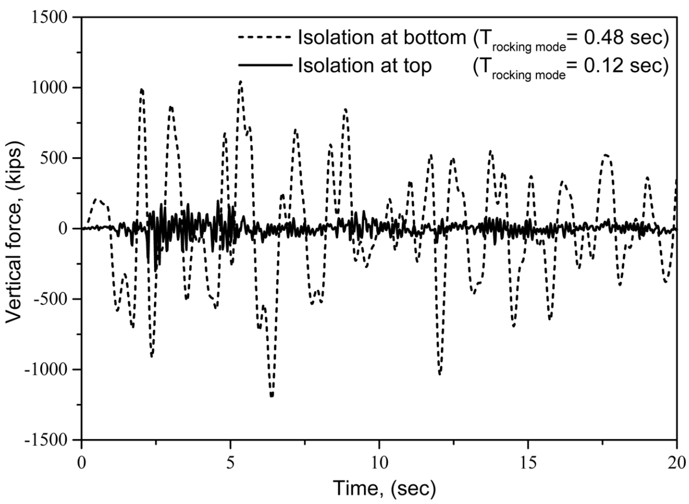

Fig. 9 Comparison of time histories of vertical force in the left cluster of isolation system when it is placed at bottom or at top of the shaft

non-isolated tank.

Placing the isolators at top of the shaft instead of placing them at the bottom causes reduction of the order of 81% in the tension forces developed in the isolators accompanied by an increase of

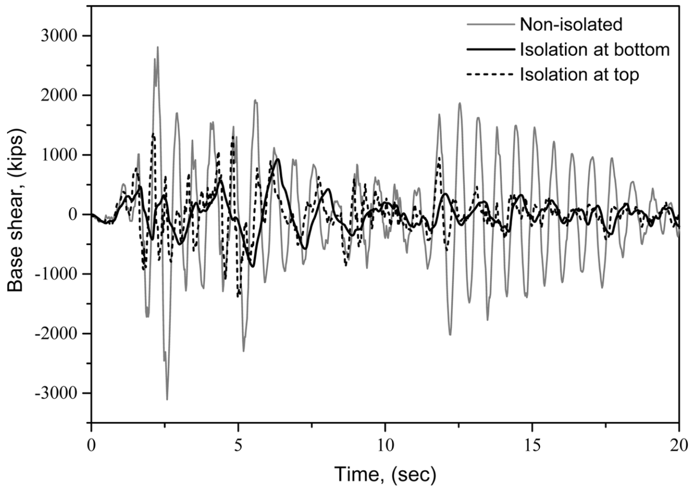

Fig. 10 Comparison of time histories of base shear for different cases

50% in the base shear. (Again, it should be noticed that the isolators in this case are designed for much less weight). Using judgment, one can conclude that placing the isolators at the top of the shaft in elevated tanks is better than placing them at the bottom. Placing the isolators at the bottom develops very high tension forces; in this case using isolators with tension load capacity is essential.

7. Conclusions

In this paper, the seismic responses of base-isolated cylindrical liquid storage elevated tanks were investigated under three real earthquake ground motions. Two types of isolation systems were considered. These are the elastomeric bearings (N-Z and HDRB systems), and the sliding isolation system (FPS system). The response of two types of tanks, namely broad and slender tanks, was obtained. The seismic response was compared with the corresponding response of non-isolated tanks to identify the effectiveness of seismic isolation of the tanks and determine the best type of isolation system. This paper also aimed to help wide spreading of the seismic isolation technology for tanks among design engineers by using SAP2000 as a common and user friendly computer program for modeling the tank involving seismic isolation systems. Lastly, the paper presented a study of the optimum location of seismic isolation in elevated tanks. This was established by studying the comparative performance of isolated elevated tanks when isolation bearings were placed at the top or at the bottom of the supporting tower structure.

From the results of the present study, the following conclusions can be stated:

- Base isolation is quite effective in reducing the earthquake response of elevated liquid storage tanks, in which reductions ranged between 60% to 80% for the base shear, and 62% to 83% for the shaft displacement, respectively. The reduction in base shear leads to reduction in the shaft wall thickness and reinforcement and hence more economic design.
- Due to enlarged period of seismically isolated tank, there is a moderate increase in the resulting convective displacement. However, such behavior has no practical consequences except for the need to increase the clear height above the liquid surface.

- Base isolation is slightly more effective for slender tanks in comparison with broad tanks.
- Performance of FPS system is better than other isolation systems.
- Modeling the isolated tanks in SAP2000 is very successful in producing results that are nearly identical to those of program 3D-BASIS-ME. Such good agreement of the results helps wide spreading of the seismic isolation technology among design engineers.
- Placing the isolators at the top of the shaft support was judged to be better than placing them at the bottom, where the vertical tension force developed in the isolators in the case of isolation at top is about 19.0% of that when the isolation system is placed at bottom.
- Placing the isolators at the bottom of the shaft support in elevated tanks develops very high tension forces in isolators. In this case using isolators with tension load capacity is essential.

References

Abalı, E. and Uckan, E. (2010), "Parametric analysis of liquid storage tanks base isolated by curved surface sliding bearings", *Soil Dyn. Earthq. Eng*., **30**, 21-31.

Almazán, J.L., Cerda, F.A., De la Llera, J.C. and López-García, D. (2007), "Linear isolation of stainless steel legged thin-walled tanks", *Eng. Struct*., **29**, 1596-1611.

Cho, K.H., Kim, M.K., Lim, Y.M. and Cho, S.Y. (2004), "Seismic response of base-isolated liquid storage tanks considering fluid–structure–soil interaction in time domain", *Soil Dyn. Earthq. Eng*., **24**, 839-852.

CSI (2005), *SAP2000 integrated software for structural analysis and design*, Analysis Reference Manual, Computers and structures, Inc., Berkeley, California, USA, Version 10.0.1.

Dutta, S., Mandal, A. and Dutta, S.C. (2003), "Soil-structure interaction in dynamic behavior of elevated tanks with alternate frame staging configurations", *J. Sound Vib*., **277**, 825-853.

Goudarzi, M.A. and Alimohammadi, S. (2010), "Numerical assessment of seismic safety of liquid storage tanks and performance of base isolation system", *Struct. Eng. Mech*., **35**(6), 759-772.

Haroun, M.A. and Housner, G.W. (1981), "Seismic design of liquid storage tanks", *J. Tech. Councils - ASCE,* **107**(1), 191-207.

Hino, J., Yoshitomi, S., Tsuji, M. and Takewaki, I. (2008), "Bound of aspect ratio of base-isolated buildings considering nonlinear tensile behavior of rubber bearing", *Struct. Eng. Mech*., **30**(3), 351-368.

Kim, M.K., Lim, Y.M., Cho, S.Y., Cho, K.H. and Lee, K.W. (2002), "Seismic analysis of base-isolated liquid storage tanks using the BE–FE–BE coupling technique", *Soil Dyn. Earthq. Eng*., **22**, 1151-1158.

Livaoglu, R. and Dogangun, A. (2007), "Effect of foundation embedment on seismic behavior of elevated tanks considering fluid–structure-soil interaction", *Soil Dyn. Earthq. Eng*., **27**, 855-863.

Maleki, A. and Ziyaeifar, M. (2007), "Damping enhancement of seismic isolated cylindrical liquid storage tanks using baffles", *Eng. Struct*., **29**, 3227-3240.

Malhotra, P.K., Wenk, T. and Wieland, M. (2000), "Simple procedures for seismic analysis of liquid storage tanks", *Struct. Eng. Int. IABSE*, **10**(3), 197-201.

Newmark, N.M. and Rosenblueth, E. (1971), *Fundamentals of earthquake engineering*, Prentice-Hall, Englewood Cliffs, N.J.

Scheller, J. and Constantinou, M.C. (1999), "Response history analysis of structures with seismic isolation and energy dissipation systems: verification examples for program SAP2000", Technical Report MCEER-99-0002, University at Buffalo, State University of New York, USA.

Shekari, M.R., Khaji, N. and Ahmadi, M.T. (2009), "A coupled BE–FE study for evaluation of seismically isolated cylindrical liquid storage tanks considering fluid-structure interaction", *J. Fluid. Struct*., **25**, 567-585.

Shenton, H.W. and Hampton, F.P. (1999), "Seismic response of isolated elevated water tanks", *J. Struct. Eng*., **125**(9), 965-976.

Shrimali, M.K. (2002), "Non-linear response of elevated isolated tanks", *Proceedings of 12th SEE*, 1441-1450.

Shrimali, M.K. (2005), "Comparative performance of elevated isolated liquid tanks", *Proceedings of the 3rd International Conference on Structural Stability and Dynamics,* June, Kissimmee, Florida.

Shrimali, M.K. (2007), "Seismic response of elevated liquid storage steel tanks under bi-direction excitation", *Int. J. Steel Struct.*, **7**, 239-251.

Shrimali, M.K. and Jangid, R.S. (2003), "Earthquake response of isolated elevated liquid storage steel tanks", *J. Constr. Steel Res.*, **59**, 1267-1288.

Tsopelas, P.C., Constantinou, M.C. and Reinhorn, A.M. (1994), "3D-BASIS-ME: computer program for nonlinear dynamic analysis of seismically isolated single and multiple structures and liquid storage tanks", Technical Report NCEER-94-0010, University at Buffalo, State University of New York, USA.

IT