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Vertical Isolation of Seismic Loads in Aboveground Liquid Storage Tanks

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ABSTRACT

This paper introduces an improved isolation system for aboveground storage tanks (ASTs). In this system, the tank shell is supported by a ring of vertical isolation systems (VIS) that dampen the rocking motion of the tank shell caused by dynamic loads. On the other hand, the forces in the vertical direction caused by the overturning moment are isolated as an alternative to the common horizontal system used for shear base isolation of ASTs. The effects of the proposed vertical isolation system on the seismic responses of the contained liquid are examined using various tank dimensions and earthquake ground motions. The finite element model (taking into account fluid-structure interaction effects) is used to simulate the contained liquid, as well as the tank shell. The results indicate that the new system could efficiently reduce the main seismic design parameters of the tanks, including base shear, overturning moment, and seismic stress in the tank shell. The sloshing wave height, however, is not significantly affected.

Keywords:
Liquid storage tank; Isolating system; FEM; Seismic design; Sloshing

1. Introduction

Storage tanks are key components of lifeline systems such as water supply and oil facilities, and thus, the seismic safety of liquid storage tanks is of considerable important. Maintaining the functionality of liquid storage tanks in the post-earthquake period is essential in ensuring the supply of water and fuel to earthquake-affected regions and in mitigating adverse effects, such as leakage of highly toxic and inflammable liquids. While the literature on seismic analysis of liquid storage tanks is extensive, methods of protecting liquid tanks against seismic loads have rarely been considered.

Insufficient performances of anchored and unanchored tanks during a past earthquake leads to the use of moderate and effective methods in seismic energy dissipating and ductile anchoring of tanks. Isolating systems improve the overall performance of structures. Isolation as a moderate rehabilitation method shift the response of the structure to a higher fundamental period and increases the damping, thus reducing the corresponding pseudo-acceleration in the design spectrum and attracting smaller earthquake-induced forces. Then, base isolation is a method to prevent tank shell buckling caused by hydrodynamic pressure during an earthquake.

One of the first studies on the base isolation techniques for seismic protection of the liquid storage tanks was done by Chalhoub and Kelly [1]. They tried to experimentally evaluate the behavior of a base isolated cylindrical water tank. Their experimental measurements indicated that the hydrodynamic pressures on the tank shell were reduced due to the isolation of the tank base. They also developed a theoretical solution from linear wave theory that was validated by their results [1]. Kim and Lee [2] introduced a semi-dynamic test method for evaluating the seismic performance of base isolation liquid tanks. They concluded that base-isolating properties should be adjusted by impulsive hydrodynamic pressures [2]. Park et al. [3] considered seismic isolation with pool-type storage tanks. For this purpose, a three-dimensional boundary finite element method was used. The study's main conclusion confirmed that the mechanical properties of the isolation system are the major parameter for the reduction value of hydrodynamic pressure produced by seismic excitations [3]. Wang et al. [4] investigated the seismic behavior of a liquid tank equipped with friction pendulum bearings. They extracted an analytical model for the analysis of a seismically isolated cylindrical storage tank. They also discussed the effects of friction pendulum-bearing properties on the dynamic response of a liquid storage tank [4]. Shrimali and Jangid [5] conducted a comprehensive study of the seismic behavior of isolated liquid storage tanks. They found that sliding systems could reduce the seismic response of liquid tanks considerably [5]. Given the widespread use of modal and spectrum analysis for design practice, they also tried to show that the seismic response of base-isolated tanks could be evaluated by modal and response spectrum analysis [6]. In the field of numerical methods, Cho et al. [7] used a numerical model to simulate the seismic response analysis of a base-isolated liquid storage tank. They used a coupled dynamic system in which the finite elements were considered for the tank structure and boundary elements were used for the liquid part. The main contribution of this study was to evaluate the effect of soil flexibility on the seismic behavior of a liquid tank. They concluded that radial displacements, as well as seismic responses, generally decrease as soil stiffness decreases [7].

Jadhav and Jangid [8] compared the effect of different isolation systems under bi-directional near-fault earthquake on the seismic performance of liquid storage tanks. Shekari et al. [9] developed a numerical model based on the boundary element method to evaluate the dynamic response of base-isolated liquid storage tanks. They reduced the dimension of the model in order to reduce the computational costs of the required analysis. Abali and Uçkan [10] investigated the behavior of both slender and broad tanks equipped with curved surface sliding bearings. The study found that a friction pendulum system could effectively control the seismic responses of the slender tank with respect to the broad tanks. Panchal and Jangid [11] considered the seismic response of liquid storage steel tanks isolated with variable frequency pendulum isolators. Some near-fault ground motions were applied as excitation records to evaluate the variation of design parameters. They discussed the effects of far-field ground motions on the seismic behavior of a liquid tank. Soni et al. [12] considered another base isolation system, a double variable frequency pendulum isolator, with liquid storage tanks. This system includes a double sliding isolation system with elliptical sliding surfaces. In this study, the governing equations of motion for an isolated tank under two horizontal ground excitations were extracted and solved. It was concluded that the differences between top and bottom sliding surfaces can noticeably affect the performance of this isolation system. Zhang et al. [13] also presented a simplified model of a liquid storage tank with multiple friction pendulum bearings and concluded that the sloshing height would not be amplified by the multiple friction pendulum isolation. Vosoughifar and Naderi [14] conducted nonlinear time history analyses to investigate the effect of the rubber isolation on the sloshing displacement and base shear response of a rectangular water tank. The results indicated that the isolation could reduce the base shear force, but its effects were not significant on the liquid sloshing height. Cheng et al. [15] proposed a simplified model for investigating the new isolating system with sliding base and displacement-limiting devices in rectangular concrete liquid storage tanks. Their results indicate that the proposed system could prevent the wall cracking and liquid overflow.

As can be seen in the literature, most studies to date focused on the isolation of base shear caused by hydrodynamic pressures exerted on a tank shell during an earthquake. However, several critical issues remain regarding the conventional horizontal isolation of liquid tanks. For example, the conventional horizontal isolation system cannot properly handle the net tension produced inside the tank shell due to the overturning moment. Moreover, the isolation of the total area of a tank bottom plate requires a rigid slab, which is more expensive. In addition, this requires equipment to restrain the tank's maximum horizontal displacement. Finally, making the connected equipment, such as interior and exterior pipes, compatible with the large horizontal displacement of an isolation system is a difficult and expensive task.

In contrast, the present paper suggests the idea of vertical isolation of a tank shell to reduce seismic hydrodynamic forces. On the other hand, the vertical forces produced by the overturning moments are directly isolated. In proposed isolation system, the tank shell is detached from the base plate and supported by a ring of vertical isolation systems (VIS). The finite element model (taking into account fluid-structure interaction effects) is used to simulate the contained liquid, as well as the tank shell. The results indicate that the new isolation system could efficiently reduce the main seismic responses.

2. Proposed Vertical Isolation System

The available base isolation systems reduce the horizontal shear forces produced by hydrodynamic pressures. In general, hydrodynamic pressures create an overturning moment exerted on the bottom of the tank shell, which results in tensile and compressive stresses exerted vertically on the tank shell. These vertical seismic stresses are the main source of elastic and inelastic buckling of the tank shell. Therefore, isolation of the tank shell in the direction of the tank rocking motion (vertical direction) can efficiently and directly reduce the seismic stress caused by the hydrodynamic overturning moment. In VIS, limiting vertical displacement of the tank wall is more manageable, in practical terms, for both slender and broad tanks. This is because, in addition to base shear forces, the net tensile forces are affected by the overturning moment created by the isolating system. These tensile forces may exceed the resistance of the horizontal isolating system, especially with slender tanks. Therefore, vertical isolation of a tank shell is preferable, in practical terms, than the conventional, horizontal method.

Eliminating the isolation of the tank base plate can eliminate the need for a solid base for isolation of the entire base plate which is required for the common horizontal system. In VIS, the tank shell is disconnected from the base plate and supported by a ring of vertical isolation systems. Then, the number of isolation elements required decreases significantly with respect to the common horizontal isolation in which the total base area must be covered by isolation elements. Disconnecting the tank shell and base plate, however, means we have to somehow prevent the possibility of liquid leaking from the bottom of the tank shell. This is challenging, but doable. For example, flexible plastic layers that adapt to the tank shell's vertical motion can be attached to the tank shell and baseplate (Figure 1a). In addition, the thin, corrugated plate can be used in an accordion shape to handle vertical motion without leakage (Figure 1b). To investigate the effectiveness of the vertical isolation system, Finite Element Modeling (FEM) is used. Details of the analyses are presented in the next sections (Figure 1c).

3. Numerical Simulation

The finite element method is used to numerically investigate the seismic behavior of vertically isolated tanks. The finite element model of the contained liquid and tank shell is presented in Figure (1c). In this model, four-node, quadrilateral elastic shell

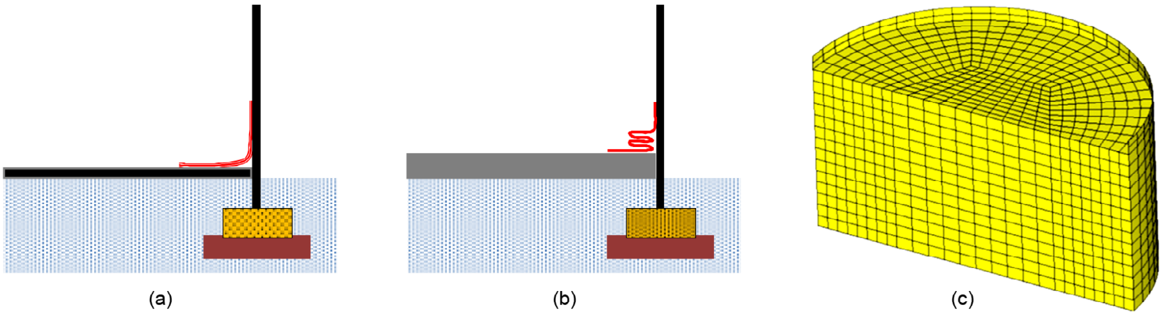

(a)
(b)
(c)

Figure 1. (a) and (b) Connection of tank shell and tank base plate in vertical direction; (c) Finite element model of tank shell and contained liquid.

elements that have both membrane and bending capabilities are used to model the tank walls. The fluid domain is modeled with three-dimensional, eight-node, fluid elements. These elements have three displacement degrees of freedoms at each node. The interaction between the tank and the fluid was addressed by properly coupling the nodes lying on the border of the two domains in the radial direction. The fluid imposes only normal pressures on the tank wall and allows for relative movements in the tangential and vertical directions between the shell and fluid elements. Fluid element nodes are also allowed to move on the surface of the tank bottom plate. Meshing of the fluid domain is undertaken so that the solid elements form shapes closest to cubes. The simulation of vertical isolation will be discussed later. Because experimental data are not available for vertical isolated tanks, the numerical model is validated only for the tank without the isolating system. The validated model is then used for the simulation of the isolated tank.

In order to verify the FEM results under seismic excitation, the results of free surface displacement obtained from the numerical model are compared with the experimental results reported by Chalhoub et al. [1]. They used a cylindrical steel tank, with a height of 60.96 cm, wall thickness of 0.001 m and diameter of 1.21 m. The El Centro earthquake record scaled by peak acceleration 0.114 g was used as an input base excitation. In Figure (2), the FEM result of free surface displacements at the shell wall is compared with the measured free surface elevation given by Chalhoub et al. [1]. There is an acceptable agreement between the FEM results and the experimental measurements.

Figure (3a) presents the assumed hysteretic loop shape of the isolator, known as bilinear response with kinematic hardening. The properties of the isolation system utilized here represent the behavior of elastomeric bearings-type isolators. For isolated structures, a fundamental period, i.e. the natural period of the structure (T_{iso}) moving as an almost-rigid body on the isolators, is generally selected in the range of 1.5 to 3 sec based on post-elastic stiffness. In order to consider the seismic isolators only under the steel ring wall of the tank, the behavior of the isolation system is modeled as vertical nonlinear springs with material nonlinearity that connects the tank wall to the ground (Figure 3b). In this study, a fundamental period of 2.5 sec is chosen for the analysis (Table 1).

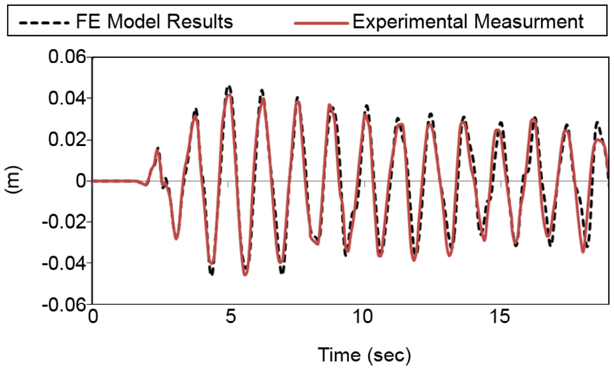
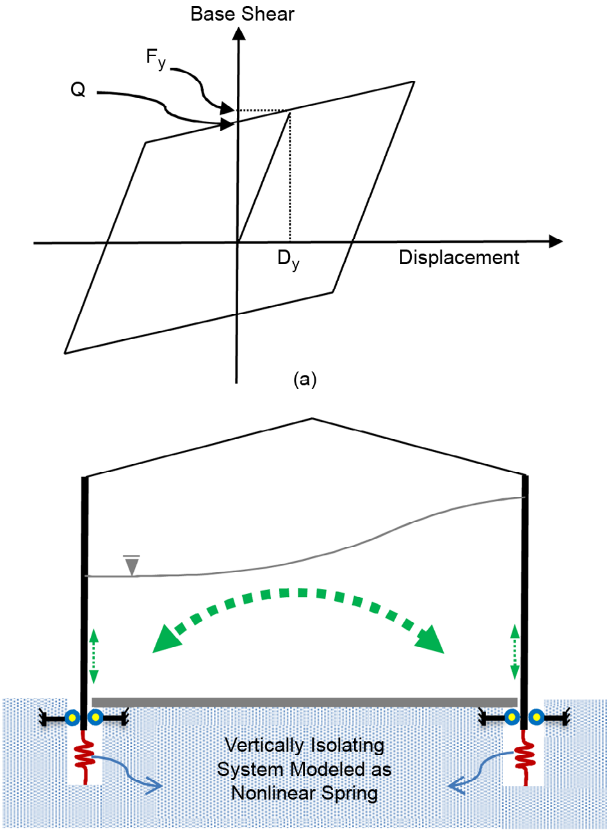


Figure 2. Comparing FEM results of sloshing wave height with experimental measurements.

Table 1. Isolation system parameters.

$E_P = M_{imp}(2\pi / T_{iso})^2$	E_P = Post-Elastic Isolation Stiffness T_{iso} = Isolation Period M_{imp} = Impulsive Mass
$E_e = (D_y . K_P + Q) / T_{iso}^2$	D_y = Yield Displacement E_e = Global Elastic Isolation Stiffness Q = Characterized Strength
$\alpha = K_P / K_e$	α = Post-Yield Stiffness Ratio
$F_y = K_e . D_y$	F_y = Global Yield Force



(a)

(b)

Figure 3. (a) Energy dissipation loop of isolators; (b) Schematic view of vertically isolating system used under the tank walls.

Table 2. Geometry dimensions of considered tanks.

	Contained Liquid	Radius (m)	Tank Height (m)	Liquid Height (m)	Lower Shell Thickness (m)	Upper Shell Thickness (m)	Liquid Density (kg/m^2)	Bulk Modulus (N/m^2)
Tank 1	Crude oil	54.5	17.5	15.85	0.03	0.03	885	1.65E+09
Tank 2	LNG	37	40.6	37.4	0.033	0.033	480	2.00E+09
Tank 3	Water	2.5	8	6.5	0.006	0.006	1000	2.10E+09

To evaluate the efficiency of the proposed VIS, the geometry and physical parameters of some real-world scale tanks are selected, and their seismic behaviors under some real seismic excitations are simulated using the introduced numerical model. For this purpose, three tanks with different aspect ratios (a broad tank ($h/R=0.3$), a medium tank ($h/R=1$), and a slender tank ($h/R=2.6$) are utilized. Each tank was designed based on the API code of practice [16]. The physical and geometric dimensions of the considered tanks are listed in Table (2).

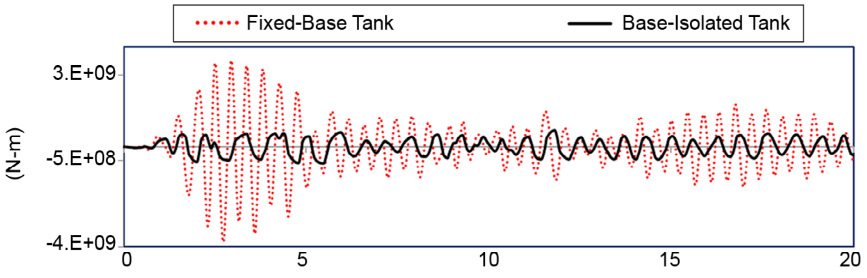
Three earthquake ground motions are chosen as the base excitations of the selected tanks in which the peak ground accelerations are considered between 3.03 and 8.3 (m/sec^2). Specifications of these earthquakes are listed in Table (3).

Table 3. Earthquake specifications used for the time history analysis.

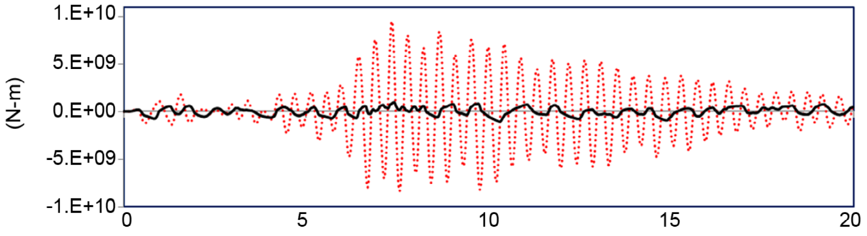
	Years	Peak Ground Acceleration (g)	Predominant Period (sec)	Abbreviation
El Centro	1940	4.1	0.5	ELSENT
Chi-Chi	1999	3.03	1.14	CHI-CHI
Tabas	1978	8.3	0.2	TABAS

4. Results of FEM Analysis and Discussions

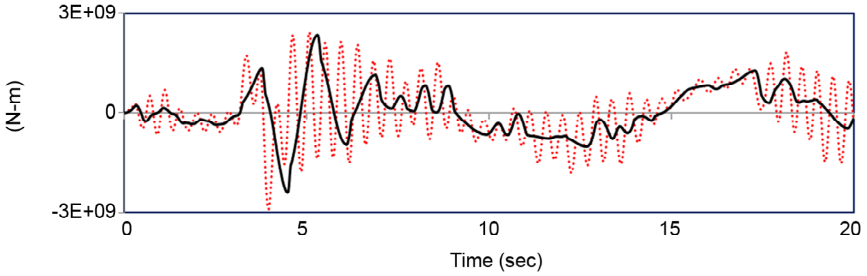
The dynamic behaviors of the tanks with and without VIS under various earthquake records are extracted from FEM analysis. As an example, the time histories of the global overturning moment of Tank 2, caused by the considered seismic excitations for the base-isolated and corresponding base-fixed medium tank, are compared in Figure (4).



(a) Overturning Moment for Tank2 (Elsent)



(b) Overturning Moment for Tank2 (Tabas)



(c) Overturning Moment for Tank2 (Chi-Chi)

Figure 4. Time history response of overturning moment for Tank 2 with and without VIS.

The overturning moment is computed with respect to the center of the cylindrical tank, neglecting the contribution of hydrodynamic pressures exerted on the base plate. As can be seen, VIS effectively reduces the global overturning moment, resulting in a substantial reduction in the stresses acting on the tank walls. The same trends were observed in other cases. In order to quantitatively compare the results, only the absolute maximum values of the design parameters (i.e., overturning moment, base shear and hydrodynamic Von-Mises stress) are extracted and presented in Figure (5).

Under the ELSENT and TABAS earthquake excitations, the mean reductions percentage in base shear and overturning moment for slender, medium, and broad tanks are 81%, 80%, and 51%, respectively. These values suggest that VIS is more effective for a higher tank aspect ratio. In the case of the Chi-Chi record, the percentage reductions in base shear and overturning moment for slender, medium, and broad tanks are 56%, 26%, and 15%, respectively. In this case, the effectiveness of vertical base isolating of the tank shells under the Chi-Chi excitation is less than that of other excitations. This is due to the fact that the Chi-Chi exaction record includes long-period motion, which leads to the excitation of the sloshing mode of the liquid. In general, the major part of a tank seismic response is caused by the impulsive mass of the contained liquid. When the sloshing mode of the liquid is excited, the contribution of convective mass to the seismic response of the tanks increases. Since the base isolation is mainly used to reduce the impulsive hydrodynamic pressure, the convective hydrodynamic pressure does not decrease considerably when using the isolating system, and may even increase. In general, it can be inferred that the effectiveness of the base isolating system depends on the value of the fundamental period of the isolation system, the predominate period of excitation, and the fundamental periods of the contained liquid. These parameters should be reasonably selected to achieve the maximum mitigation of seismic response. The results make clear, however, that VIS can be a very effective method to control the seismic behavior of a liquid tank.

The time history of sloshing wave height response of vertical-base isolated tanks and corresponding

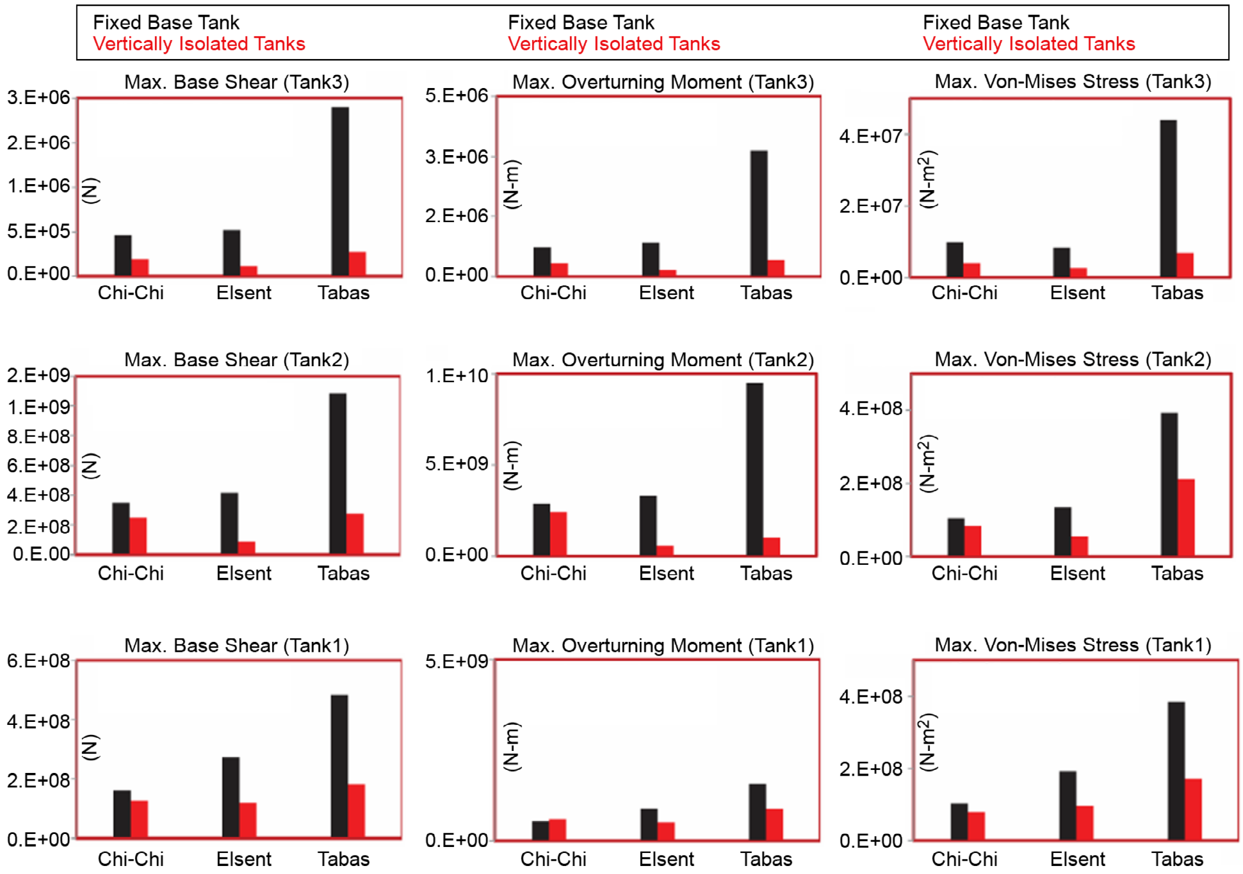


Figure 5. Time history response of overturning moment for Tank 2 with and without VIS.

fixed-base tanks for the TABAS earthquake is plotted in Figure (6). As can be seen, the average surface motion period is close to the first convective mode of contained liquid, implying that the significant hydrodynamic sloshing motion is dominated by the fundamental convective modes. Whether or not the time history of the sloshing wave is considered, Maximum Sloshing Wave Height (MSWH) is generally considered a major parameter in the seismic design of liquid storage tanks. MSWH is used to provide sufficient freeboard between the liquid surface and the tank roof to prevent sloshing wave impact. If sufficient free board is not provided, the tank roof should be designed against roof forces [17].

The FEM results of MSWH for vertically isolated and corresponding fixed-base tanks are compared in Figure (7). As can be seen, VIS cannot substantially change the sloshing wave height except with the slender tank (Tank 3). For Tank 1 and Tank 2, the fundamental period of convective mode is far enough from the period of VIS. Therefore, the sloshing motions shown in Figure 7 for these tanks are quite similar in both fixed base and base-isolated tanks. In the case of the slender tank; however, the sloshing period is close to the vertical isolation period, and it is expected that the sloshing motion considerably affected by isolating the tank wall.

The plots in Figure (8) show the deformation of three vertically isolated tanks caused by the Elsent earthquake excitation. The deformation in the vertical direction has a maximum value of 11.6 cm,

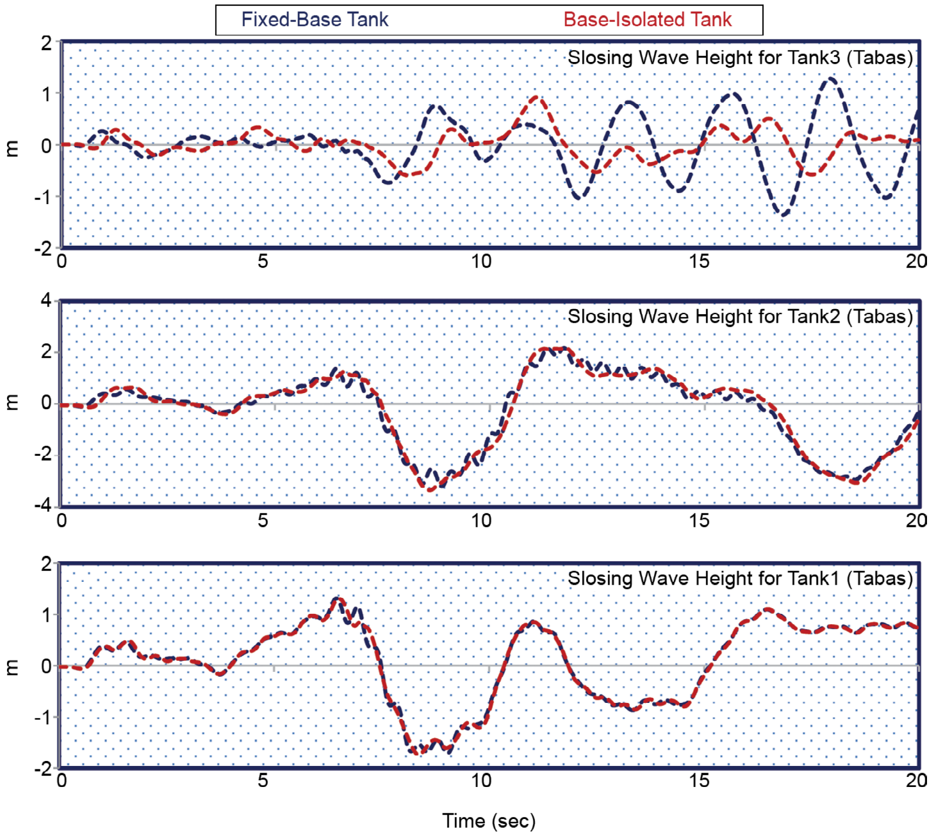


Figure 6. Time history response of overturning moment for Tank 2 with and without VIS.

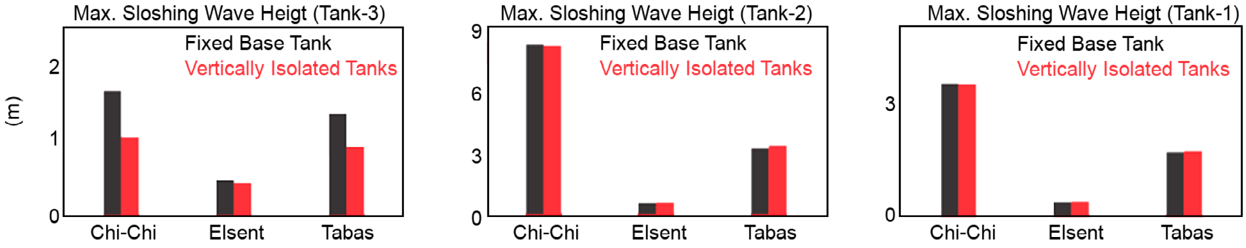


Figure 7. Maximum sloshing wave height for fixed and vertically isolated tanks.

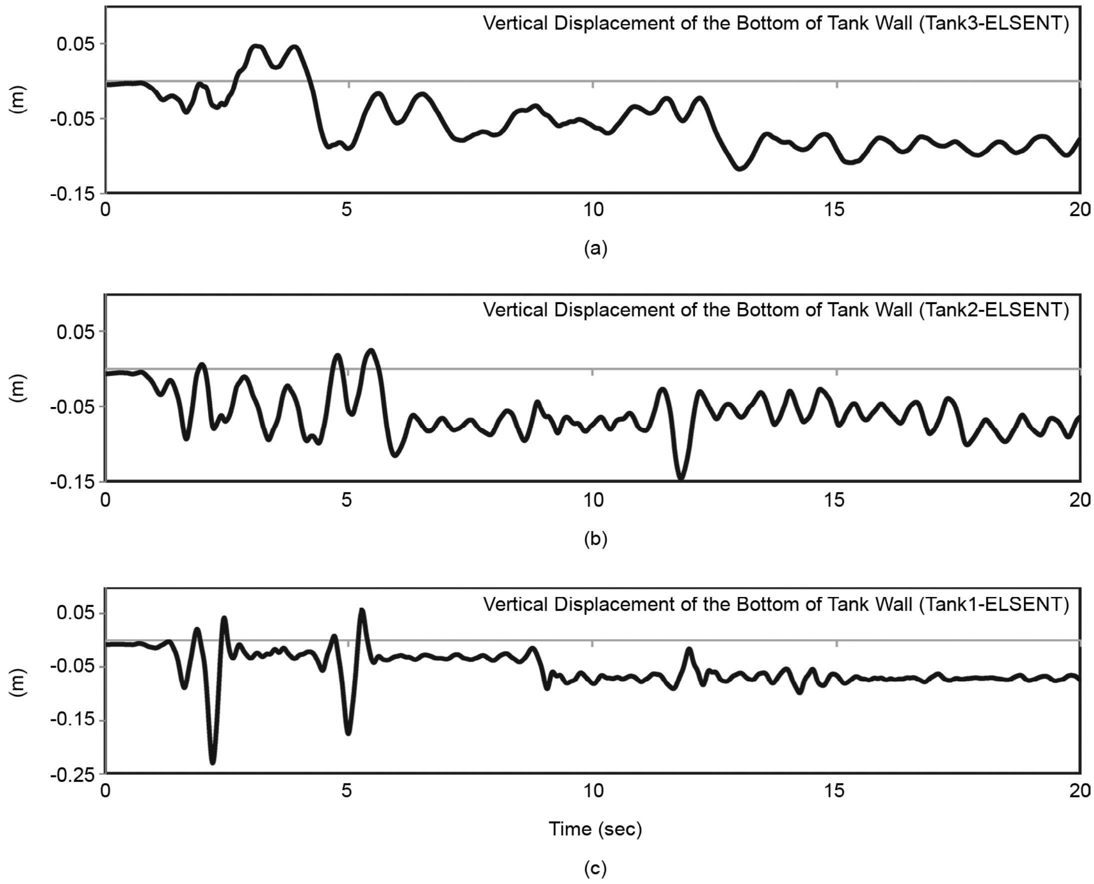


Figure 8. Time history of vertical displacement of isolation system under the ELSENT earthquake.

14.5 cm, and 23 cm for the slender, medium, and broad tanks, respectively. These results suggest that vertical isolation of the tank wall is quite effective for Tank 3 and Tank 2. For the broad tank (Tank 1), however, vertical isolation of the tank wall leads to a smaller reduction in seismic loads (discussed in previous sections) and larger vertical displacement of the tank base. The vertical displacement of VIS is important for preventing fluid leakage from the bottom of a disconnected tank wall.

5. Conclusions

Vertically Isolation system (VIS) is proposed to reduce the hydrodynamic pressures caused by seismic loads. In this method, only the tank shell (instead of the whole tank base plate) is vertically isolated, and the tank shell should be disconnected from the base plate. The finite element method is used to evaluate the efficiency of the suggested isolating method. For this purpose, the seismic behavior of three vertically isolated and non-isolated tanks under several earthquake excitations are evaluated by numerical simulation. The results indicate that isolating a tank shell in the vertical direction effectively reduces the base shear and hydrodynamic overturning moment exerted on the base of the tank, which results in a substantial reduction of the seismic stresses acting on tank wall. For the physical and geometrical parameters used in this study, the mean percentage reductions in base shear and overturning moment were 81%, 80%, and 51% for a slender, medium, and broad tank, respectively. Therefore, VIS can be regarded as a shell buckling retrofitting method in liquid storage tanks.

Sloshing wave height responses were not affected by the introduction of the VIS when the periods of the isolated and convective modes were well separated, which was true for most liquid storage tanks.

It is observed that a net tensile force is generally experienced in a tank shell (especially in a slender tank) during a strong ground shaking. Therefore, vertical isolation of the tank wall is a quite effective system for these liquid storage tanks. For the broad tank, however, a lower reduction in seismic forces and higher vertical displacement of the tank shell is observed. Therefore, the proposed vertical isolation system may be more effective for slender and medium tanks.

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