Behavior of the Liquid Storage Tank Under Coupled Effect of Bidirectional Excitations and Angle of Incidence of Earthquake

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Abstract The liquid storage tanks (LSTs) are the paramount structures in oil, nuclear and various chemical industries. The structural properties and sloshing of stored fluid can significantly alter the nature of the seismic response. Several failure incidences of LSTs are available in history because of earthquakes. Despite exhaustive research on this topic, the behavior of the rectangular steel LSTs under the near-field earthquake and long period far-field earthquakes demands more attention for a more stable design. The finite element (FE) analysis of LST is done on the ABAQUS platform. The behavior of the LSTs is studied by varying the angle of incidence of the earthquakes and the ratio between the different components of the earthquake. The resultant response due to bidirectional interaction and angle of incidence shows an increase in sloshing height; von Mises stress and top board displacement.

Keywords Bidirectional excitation · FSI · Angle of incidence · FEM · Coupled acoustic-structural approach · LSTs

1 Introduction

The liquid storage tanks are regarded as one of the most important civil and industrial structures. They can be divided into various groups such as underground, elevated and simply fixed to the ground, or depending on the construction material they can be further classified as steel or concrete tank. The ground supported liquid storage tanks (LSTs) are widely used for storing chemical, nuclear material, and water. The exposure of the ground supported steel rectangular LSTs to the seismic hazards is a

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matter of concern, as failure in the LSTs can result in a disaster of huge magnitude. The most common failures seen in the failed structures were elephant foot buckling, damage of the roof and uplifting of the LST base. Some of these failures were reported in the Alaska earthquake, Alaska, (1964), Tabas earthquake, Iran (1978), Sierra Madre earthquake, California (1991), Hokkaido earthquake, Japan (2003), Sumatra Earthquake, Indonesia (2004), Yushu earthquake, China (2010) and Central Mexico earthquake, Mexica (2017). The continuous research on the seismic response of the ground supported LSTs has shown the current design philosophy of LSTs has some shortcomings.

The analysis of an LST can be divided into two different sections, i.e. impulsive and convective parts. The impulsive response contributes to the major part of the shear forces, overturning moments, stress in tank walls whereas, convective response provides the sloshing response which is responsible for the roof damage in the LSTs. For a complete behavioral analysis of the LSTs under the excitations, both impulsive and convective responses need to be studied. This combined response of impulsive and convective gives pressure on the tank wall and the base shear force of the LSTs. Thus, to determine the safety in the steel LSTs, an updated approach is required.

The past approaches for the LSTs models can be grouped under the 2D or 3D models, and numerical or analytical. Housner [1, 2] presented results in the closed-form of mathematical expressions for both elevated and ground supported tank. Some other analytical expressions were given by various researchers (Gupta and Hutchinson 1988; Fischer and Seeber 1988). Several numerical method and techniques were developed to study the dynamic behavior of LSTs which were verified by the experimental analysis by many notable researchers [3–8].

Many studies were made on the dynamic response of LSTs under the earthquake motion using FEM. The FEM approach taken by researchers provides the exhaustive analysis of fluid–structure interaction (FSI) by different FEM elements [9–19].

In the most recent past, Kianoush and Ghaemmaghami [20] studied the three-dimensional FSI and SSI which was numerically simulated using FEM for a partially filled concrete rectangular tank for different ground motion records. The response quantities were base shear, base moments and sloshing height. Mandal and Maity [21] discussed the effect of change of horizontal harmonic excitation frequencies and amplitudes. The author reported that altering the magnitude of the harmonic excitations developed the nonlinear responses. However, the linear and nonlinear hydrodynamic pressures were not significantly affected. Bakalis et al. [22] designed the three-dimensional surrogate model, which can be used to investigate the multidirectional support system for both the fixed and pinned tanks. The results of the study were validated by the existing experimental results. Zhang and Wan [23] investigated the effect of Young's modulus of the tank wall on the sloshing phenomenon. The study was carried out by the application of a fully lagrangian FSI solver. The solution to the impact of the sloshing wave on the tank wall with smaller Youngs modulus took more time than that for rigid wall tank. Rawat et al. [24] investigated the coupled acoustic-structural (CAS) and Euler–Lagrange approach (CEL) of FE approaches to simulate the sloshing effect in a steel cylindrical liquid storage tank. Although both the methods yielded identical results, it was concluded that the CAS approach was more numerically efficient. Jin and Lin [25] studied the viscous effect of the fluid sloshing due to the external excitations. The sloshing motion was captured by a 3D numerical model NEWTANK which employs spatially averaged Navier–Stokes equations and large eddy simulation approach. Moslemi et al. [26] studied the nonlinear sloshing in rectangular storage tank. The effect of the different parameters was taken in the consideration such as tank aspect ratio, bidirectional loading and earthquake frequency.

With help of FEM suites like ABAQUS and ANSYS, the analysis of LSTs under seismic excitation becomes more accurate and realistic. For understanding the FSI in the LSTs various FEM elements are present. Among the available FE elements, acoustic elements are selected because of their low cost.

Despite the various studies available in the research community on the LSTs, the studies for the rectangular steel tanks are still very less, and its behavior under the bidirectional interaction is even less. The present research focuses on the FEM approach of the square steel tanks under the bidirectional interaction of different types of earthquakes (far-field and near-field). The coupled effect of the structural geometry with the angle of the incidence of the earthquake is also examined to determine the critical angle of incidence of the earthquake. The different response quantities under study include base shears, overturning moments, sloshing height and top board displacement in the tank.

2 Theory

The response of the liquid storage tanks subjected to the earthquake ground motion develops a nonlinear and complex FSI. Due to the sudden application of the ground motion, a very high magnitude of the inertial forces is generated in the tank walls. Due to the hydrodynamic pressure on the tank walls the resistive inertial forces get amplified. The flexibility of the tank walls further pushes the fluid media which develops an overall imbalance in the liquid media. Due this imbalance the tank material is further pushed into the nonlinear domain. To simulate the nonlinearity, behavior of the FSI ABAQUS uses an implicit operator. For solving the nonlinearity in the solution, Newton's method is used as its convergence rate is faster than any other method. For a solution iteration an i approximate solution is approached, u_i^M and C_{i+1}^M is defined as the difference of the solution and is the exact solution for the discrete equilibrium equation,

$$F^N(u_i^M + c_{i+1}^M) = 0 \tag{1}$$

Form the expansion by the Taylor series with respect to the solution approximation u_i^M, the following equation is achieved.

$$F^N(u_i^M) + \frac{\partial F^N}{\partial u^P}(u_i^M)c_{i+1}^P + \frac{\partial^2 F^N}{\partial u^P \partial u^Q}(u_i^m)c_{i+1}^P c_{i+1}^Q + \cdots = 0 \tag{2}$$

If the solution of each step u_i^M is in close approximation, then the magnitude of each C_{i+1}^M will be small. By neglecting the initial two terms of the equation gives a linear system of equations as,

$$K_i^{NP} c_{i+1}^P = -F_i^N \tag{3}$$

$$K_i^{NP} = \frac{\partial F^N}{\partial u^P}(u_i^M) \tag{4}$$

$$P = \frac{\pi^2 E I_y}{L^2} \tag{5}$$

If Eq. (3) is the Jacobian matrix and $F_i^N = F^N(u_i^M)$, then the equation of next iteration is given by

$$u_{i+1}^M = u_i^M + c_{i+1}^M \tag{6}$$

The convergence of solution is measured by ABAQUS by ensuring that all values of F_i^N and c_{i+1}^N are small. After checking the conditions, ABAQUS provides the peak values of force residual and displacement.

2.1 Details of Finite Element Modeling

The present FE analysis is performed for a typical rectangular liquid storage tank. The LST is fixed at the base. To understand the complex FSI due to the seismic ground motion coupled acoustic structure, FE formulation technique is adopted. The fluid is modeled by acoustic continuum three-dimensional eight-nodded brick element (AC3D8R). The tank is modeled by a regular four-nodded quadrilateral shell element with reduced integration (S4R). For accurate results a mesh convergence study is carried out; the minimum mesh size of 0.125 m is selected.

The use of the acoustic element in FSI is advantageous because it has only one degree of freedom, which reduces the computational time. The suitable boundary conditions are applied between the inner tank surface and a fluid outer surface. The boundary condition facilitates the transfer of energy and momentum in the fluid media from tank walls. The top fluid surface requires a different surface condition to incorporate the sloshing effect. The boundary impedance condition is applied at the top of the free surface of the fluid. This boundary condition at the free surface is defined as:

$$\dot{u}_{\text{out}} = \frac{1}{k_1}\dot{p} + \frac{1}{c_1}p \tag{7}$$

Here, $\dot{u}_{\text{out}}$ is known as acoustic particle velocity, which is in normal outward direction of the acoustic medium surface; p is acoustic pressure; $\dot{p}$ is the time rate of change of the acoustic pressure. The value of coefficient $1/k_1$ and $1/c_1$ are calculated with respective fluid properties [27]. A dynamic implicit procedure with automatic time incrementation technique is selected as per the problem requirement. For simulating the seismic motion in the tank, an acceleration time history is applied as an acceleration boundary condition in the base of the tank. A couple of dynamic procedure steps are created to model the nonlinear dynamic behavior in tank. The interaction between the tank wall motion and liquid motion is a tie constraint, in which the master surface is tank wall, and water surface is slave surface.

The earthquake motions consist of two major groups, far-field and near-field excitations. Furthermore, to extend the understanding, near-field (NF) earthquakes are extended into primarily three groups, and those are NF-fling step, NF-low directivity, and NF-high directivity. The criteria for the NF earthquakes are the Joyer Boore distance (R_{jb} < 15 km). In the present study, the behavior of the LST under the bidirectional excitation for the array of near-field and far-field earthquakes is studied. The response of near-field is quite different than the far-field response, near-field earthquakes have large amplitude of the acceleration and the frequency range of the near-field earthquakes is limited. The fling step earthquake has the strike-slip rapture fault direction parallel to the strike and a significant monotonic step in displacement time history. The directivity of the near-fault earthquake arises when the rapture direction is toward the structures.

3 Numerical Study

For the numerical study, a steel rectangular liquid storage tank is considered. The tank is subjected to bidirectional earthquake excitation at the base. The tank is a plan square geometry with length of 6 m and height being equal to 4.8 m. The thickness of the tank wall is taken as 0.0152 m. The tank is considered as partially filled up to a height of 3.6 m with h/L ratio of 0.75 where h is fluid height and L is the tank length. The various material properties taken in the analysis are given in Table 1.

For the proper assessment of the stresses in the tank wall and other responses of interests, three different types of the near-field earthquakes are taken, whereas, for the far-field response, a single time history is taken up for the analysis. Table

Table 1 Material properties

Steel	Water
Modulus of elasticity, E_s = 200 GPa	Density, $\rho_w = 983.204$ kg/m^3
Density $\rho_s = 7900$ kg/m^3	Bulk modulus, $K = 2250$ MPa
Poisson's ratio, $\upsilon = 0.33$	

Table 2 Properties of various earthquakes

Earthquake	Recording station	Magnitude
Kern County (1952)	Taft Lincoln School	7.3
Imperial Valley (1940)	El-Centro	6.6
Kocaeli (1999)	Sakarya	7.5
Parkfield (2004)	Chalome 1E station	6.0

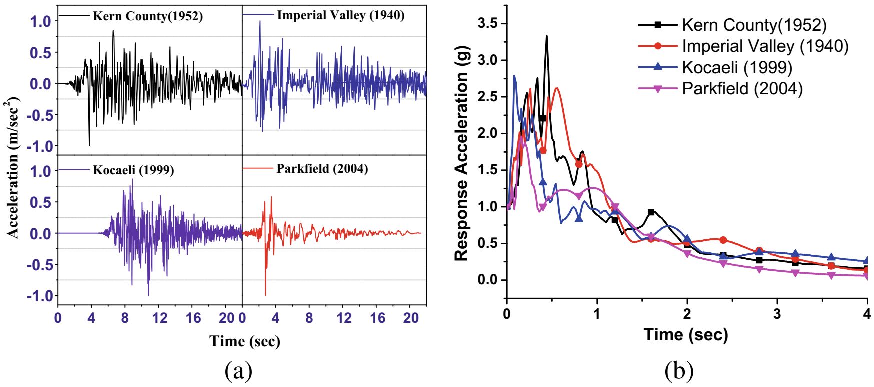

Fig. 1 **a** Earthquake time history plot. **b** Response spectra plot

2 illustrates various earthquakes taken in present study along with their recording stations (Fig. 1).

3.1 Validation of the FEM

To validate the current FEM results, an FE analysis is done in which, the tank and water are modeled by a two-node linear beam in a plane (B21) and a four-node bilinear plane strain quadrilateral (A2CD4) finite element programmed in ABAQUS, respectively. Figure 2 displays the obtained sloshing height time history. The results are determined at the right-side node of the fluid media. The sloshing height in Fig. 2 lucidly shows that the responses from the current FE method are in excellent agreement with the existing FE solution [17] for an extended period of analysis time.

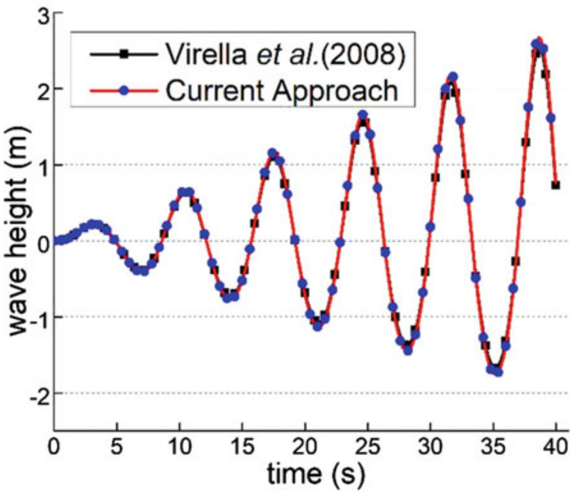

Fig. 2 Validation of FE approach

3.2 Comparison Between Unidirectional and Bidirectional Responses

To illustrate the importance of the bidirectional interaction in the earthquake analysis, the LST is examined for the unidirectional effect, and then the contrast is made between the bidirectional excitation. Figure 3a, b gives the percentage change in the von Mises stress, base shear, base moment and sloshing height. These values are taken as the absolute maximum value of the response. For calculating the maximum, von Mises stress comparison between uni and bidirectional response is extracted at the base of the tank. There is a change in the value for the von Mises stress. There is a notable increase of 12% when bidirection excitation is studied. The effect of the nature of the earthquake can be seen, maximum increase can be observed in the case of the Kocaeli earthquake. This difference is minimum for the shear force. It can be seen from the figures that Kern county earthquake shows more difference for the von Mises stress whereas, shear stress, base moment and sloshing height display lowest change in the present group of the earthquake.

The base shear and overturning moment show a change of 4–8%, which is very low, whereas sloshing height shows a notable change of 50–70%.The increase in sloshing height points to the need for the importance of the bidirectional interaction. The sloshing height change is maximum for the Kocaeli earthquake with 70% increase with respect to the unidirection excitation. Thus, these results lucidly indicate that the effect of the near-field earthquake is more devesting then the far-field earthquakes.

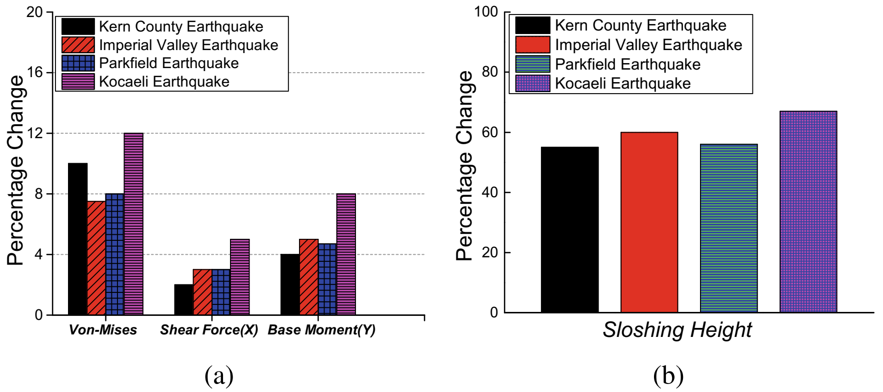

Fig. 3 Percentage change in **a** von Mises stress, shear force (X) and base moment (Y) **b** Sloshing height

3.3 Effect of Incidence Angle on Responses of LST

The impact of the angle of incidence of earthquake on the various outputs is shown in Fig. 4. The six variations of angle of the incidence earthquake are studied for the steel LST under bidirectional excitation of the earthquake with a PGA level of 0.4 g and 0.27 g in X and Y directions, respectively. It can be seen from the figure that von Mises stress varies mildly at an angle of 30° to 45°. The maximum value of the von Mises stress can be seen for the Imperial valley earthquake which is a near-field earthquake. The sloshing height also varies with angle of the incidence. The peak sloshing height is achieved at an angle of 0°.

The variation of the maximum shear force and overturning moment remained unchanged toward the angle of the incidence. The maximum value of the base shear and the overturning moment is observed for the Kocaeli earthquake, thus while examining responses in LSTs, it is important to also study the nature of the earthquakes.

The absolute top board displacement variation in *X*-direction is as shown in Fig. 4. It can be seen from the figure that angle of earthquake has a significant impact. The top board displacement attains a maximum magnitude at 60° angles. Here again, the maximum top board displacement is observed for the near-field earthquakes, whereas minimum is for the far-field earthquakes. The above results indicate that bidirectional interaction effect along with impact of the angle of the incidence should be considered to identify the most critical cases for the analysis of steel LSTs under the seismic excitations.

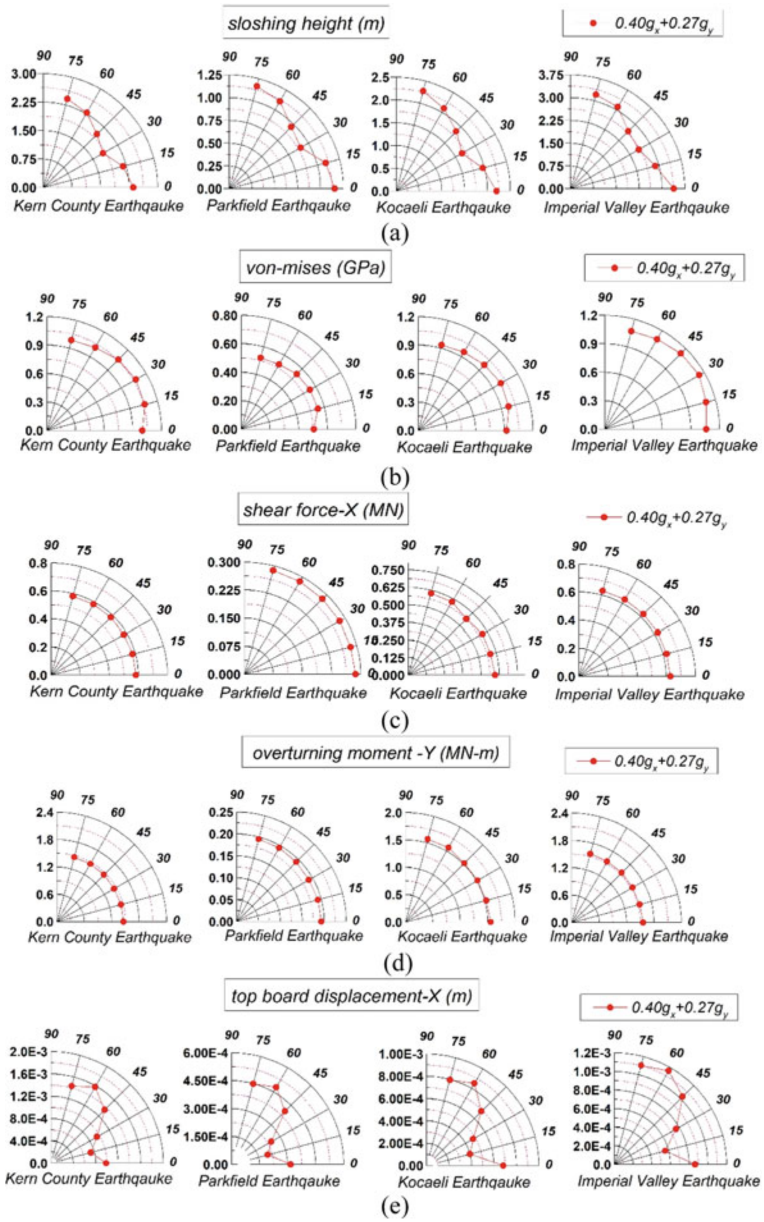

Fig. 4 Change in responses with angle of incidence. **a** Sloshing, **b** von Mises stress, **c** Shear force (X), **d** Base moment (Y) and **e** Top board displacement (X)

4 Conclusions

The dynamic analysis of steel LSTs under the far and near-field earthquake is investigated. The different parameters include overturning moment, base shear, sloshing height, top board displacement and von Mises stress in tank. For the numerical case study, a steel square tank of dimension 6 m × 6 m × 4.8 m is taken. The FE study is carried out on ABAQUS software. For reliable results, the current acoustic approach is verified with previously available results. The results lead to the following conclusions.

1. The bidirectional interaction indicates an overall increase in the response quantities, the significant increase of 45–70% is seen for the case sloshing height.
2. The maximum increase in the responses is observed for the near-field earthquakes, particularly for the fling step earthquakes.
3. The base shear, the overturning moment remains unchanged for the different angle of incidence, whereas the von Mises stress values showed an increase for the 45° angle configuration.
4. The effect of the angle of incidence is observed to be significant for the sloshing height, top board displacement, the sloshing height gets reduced at the angle of 45° whereas, top board displacement attains a minimum value at initial angle configuration, after that it goes on increasing with a decrease at the 60° angle.

The results of the study indicate that for a more critical assessment of LSTs behavior under earthquake motion requires an exhaustive analysis in the form of reliability analysis.

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