Behavior of Liquid Storage Tank Under Multidirectional Excitation

Sourabh Vern, Mahendra Kumar Shrimali, Shiv Dayal Bharti, and Tushar Kanti Datta

Abstract By revoking the effect of vertical component in the analysis of different response quantities of LST may differ from the true response of structure during a seismic event. This paper aims to study the effect of the vertical component of an earthquake on various response quantities, namely tank wall displacement, surcharge at the free surface of the water, overturning moment, and base shear. The study is compiled with the help of nonlinear time history analysis in an explicit finite element module on ABAQUS platform. For illustration, a 10-m long-rectangular liquid storage tank has been modeled by using a solid element with fluid medium modified by the arbitrary Lagrangian and Eulerian (ALE). Investigation for response is done first with bidirectional and then with the vertical component is considered. Some notable conclusions of the study include vertical component alone, which increases the responses to an order of about 30%.

Keywords FEM · Liquid storage tanks · ALE · FSI

1 Introduction

An important civil structure must be able to keep functioning or should be partially able to work even after an earthquake hazard because the complete collapse in any life-supporting structures can be very damaging for the recovery of a nation from the disaster. One such important structure are liquid storage tanks (LST): the omnipresent

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application and implementation rivet extra attention than that of normal load-bearing structures. There are several historical evidence that show that failures of LST are proven deadly, and their repercussions can last from a few months to more than a decade. Few such examples in which LST are witnessed to collapse are 1933 Long Beach Earthquake, California, USA; 1960 Chile Earthquake, Chile; 1964 The Great Alaska Earthquake, Alaska, USA; 1978 Miyagi Prefecture Offshore Earthquake, Japan; and 2003 Tokachi Offshore Earthquake, Japan. As most of these tanks are used to store liquefied gases and fluids which have a lower flash point a simple spark developed by contact between tank roof and wall can set a full surface fire in the tank.

Authors in the past have taken different approaches to tackle analysis of this problem. Housner [1] represented more defined and exact analyses in which pressure can be subdivided into two major parts, Convective and Impulsive. Impulsive pressure is exerted by the inertial response of the fluid which is because of the inertial response of the tank walls. Whereas the convective response is produced due to the oscillation of the liquid. The author presented a simplified procedure which has been prescribed by API standard 650 [2]. Additional information for measuring the sloshing height, the impact forces due to the sloshing on the columns of the roof is given along with the change in the magnitude of the hoop tension due to the earthquake ground motion. the shift in the design approach is observed from the Housner's rigid tanks in which pseudo-acceleration's spectral value is taken instead of maximum ground acceleration.

Taken up the fluid–structure interaction inside a liquid storage tank by finite element method with emphasis on dynamic and buckling analyses [3]. Lagrangian–Eulerian kinematical description for modeling fluid subdomains in fluid–structure interaction problems, the finite rotation effects in the numerical integration of constitutive rate equations arising in large deformation analysis and the implicit-explicit finite element techniques for transient analysis. Disarray is reported while extracting response for high Reynolds number flows and complex shell buckling. Malhotra et al. [4] explained the design criteria for the simplified cylindrical ground support liquid storage tank. While examining the design criteria, impulsive and convective part of the liquid in flexible steel or concrete tanks fixed to rigid foundations is considered. Virella et al. [5] extracted the sloshing natural periods and their modal pressure distributions by the influence of nonlinear wave theory for two-dimensional behavior rectangular tanks. Cao et al. [6] studied the paralleled SPH codes are programmed to study the liquid sloshing in both two-dimensional and three-dimensional tanks of single and multi-degrees of freedom. A dynamic response analysis of vertically excited liquid storage tanks including both liquid-tank and liquid-soil interaction [7]. The ground excited tank-liquid-soil system is transformed by the generalized-coordinate approach' I and then it is analyzed by the complex frequency response method.

Evaluate dynamic response of an elastic circular cylindrical tank having a rigid base under a vertical excitation taking into consideration the interaction with the foundation soil, a more representative solution for the problem in the frequency domain is obtained where the soil is appropriately modeled by frequency-dependent parameters [8]. The effects of vertical excitations have shown that significant hoop stresses can be developed in the walls of liquid storage tanks, and for intense motion, these cannot be ignored in comparison with the hydrostatic hoop stresses used in the design of such tanks. Presented a technique for evaluating the dynamic response of an upright circular cylindrical liquid storage tank to a vertical component of ground shaking, considering the flexibility of the supporting medium [9]. It is shown that soil-structure interaction reduces the hydrodynamic effects and that the consequences of such interaction may be approximated with good accuracy by a change in the natural frequency of the tank-liquid system and by an increase in damping. Investigated the method for analyzing the earthquake response of elastic, cylindrical liquid storage tanks under vertical excitations [10]. Tank response under the simultaneous action of both vertical and lateral excitations is calculated to evaluate the relative importance of the vertical component of ground acceleration on the overall seismic behavior of liquid storage tanks. It should be noted that vertical excitation is important in the seismic analysis of reinforced concrete tanks since these structures are more susceptible to the increase in hoop stresses.

Kianoush and Chen [11] conducted the study to determine the response of concrete rectangular liquid storage tanks subjected to vertical ground acceleration is investigated. The maximum response due to vertical acceleration can be as high as 45% of that due to the horizontal component. It is concluded that the effect of the vertical component of ground motion should be considered in the analysis of rectangular tanks for liquid containing structures. This is especially of significance for the near-field zones which require further investigation. Ghaemmaghami and Kianoush [12] developed the finite-element method is used to investigate the seismic behavior of rectangular liquid tanks in two- dimensional space. The method can consider both impulsive and convective responses of the liquid-tank system. Also, applying the vertical excitation will lead to an increase in the convective response of the system. However, it does not affect the impulsive behavior significantly. This increase is more noticeable in tall tank mode. Morris et al. [13] reported a baseline of the percentage increase when switching to the vertical response period and an understanding of how each of the different code's provisions can impact the design forces. As other codes move to adopt the design vertical response spectrum the provisions used to predict the demand should also be reviewed for accuracy.

For controlling the responses of the liquid storage tank, there are several techniques that are being employed in the tanks. Common approach witnessed by several authors is to construct various types of obstruction inside the tank or along the wall to prevent or completely stop the sloshing of the inertial mass of the fluid due to earthquake ground motion. Stricklin and Baird [14] surveyed the Miles' method for determining the damping produced by ring baffles in cylindrical tanks was conducted. O'Neill's modification of Miles' equation which eliminates free surface wave height from this equation is determined. The potential of baffles in increasing the hydrodynamic damping of sloshing in circular-cylindrical storage tanks is investigated, the ability of baffles in reducing the sloshing effects in storage tanks that are especially broader than fuel containers were under question [15]. A numerical model has been developed to study three-dimensional (3D) liquid sloshing in a tank with baffles [16]. The numerical model solves the spatially averaged Navier–Stokes equations. Systematic numerical simulations are carried out to investigate the sloshing dynamics of liquid in a storage tank, subjected to seismic excitation [17]. To suppress the free surface fluctuations and the associated slosh force, two types of baffles viz., ring and vertical baffle are examined. Spectral analysis of free surface displacement and temporal variation of pressure demonstrate dominant contribution from the fundamental sloshing mode.

Another method which seems to have high reliability and a longer lifespan is the isolation of the structure. The isolation of superstructure can be developed by use of a passive device commonly referred to as base-isolator at the base. There are several base isolation techniques, but due to their large area of applications only two stands out. First being the lead rubber bearing (LRB) and the second is the frictional pendulum system (FPS) which is a sliding type of isolator. A parametric study is conducted to study the effects of important system parameters on the effectiveness of seismic isolation of the liquid storage tanks [18]. It has been found that the bi-directional interaction of frictional forces has noticeable effects and if these effects are ignored, then the sliding base displacements will be underestimated which can be crucial from the design point of view. The seismic response of liquid storage tanks isolated with variable friction pendulum system is investigated under six recorded near-fault ground motions [19]. To improve the safety of concrete RLSS under earthquake action, an energy dissipation method of sliding isolation and limiting devices for concrete RLSS is proposed, the dynamic responses of sliding isolation concrete RLSS under bidirectional earthquake are studied [20].

The present study aims to investigate the effect of the tri-directional earthquake motion on a liquid storage tank and compare the response quantity of interest with that of the bi-directional earthquake. Thus, by concluding the change in the response quantities by the vertical component of the earthquake. The effect of vertical component is studied for two strong ground motion and one little weaker ground motion, to conclude the vertical component will result in an increase of response quantities in both cases.

2 Methodology

The analysis of the liquid storage tank under the earthquake motion involves different physical phenomena. In the sloshing motion, the major part of the interaction is the motion of the container. Apart from the interaction between the two different states namely, liquid and solid, there is the interaction of the fluid media with itself which causes the ripple effect which in effect increases the sloshing height.

For a nonlinear solution, a method for analysis required for extracting response quantities must be able to handle the non-linearity effect along with fluid–structure interaction (FSI). Thus, a robust finite element application method is adopted for long duration nonlinear time history analysis.

The non-linearity is solved in ABAQUS by the help of explicit central-difference integration rule. The simplicity in solving the problem doesn't provide the necessary computational efficiency which is involved with the explicit dynamic procedure. The input of the diagonal mass matrix at initial of the time step increment are resulted from the Eq. (1)

$$\ddot{u}^{N}_{(i)} = \left(M^{NJ}\right)^{-1}\left(P^{J}_{(i)} - I^{J}_{(i)}\right) \tag{1}$$

Here M_{NJ} is the mass matrix, P_J is the load vector, and I_J is the force vector. As given in the Eq. (2) the inverse of the lumped mass matrix is first solved, the number of iterations requires for the solution is equal to the number of degrees of freedom which is obtained by the multiplication between the inverse of the mass matrix and the inertial force.

$$\dot{u}^{\left(i+\frac{1}{z}\right)} = \dot{u}^{\left(i-\frac{1}{z}\right)} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2}\ddot{u}^{(i)} \tag{2}$$

$$\dot{u}^{(i+1)} = \dot{u}^{(i)} + \Delta t^{(i+1)}\dot{u}^{\left(i+\frac{1}{2}\right)} \tag{3}$$

The equation of motion for the solution is integrated using the central difference integration rule as stated in Eq. (2), where $\dot{u}$ and $\ddot{u}$ are the velocity and acceleration values respectively. The superscript (i) indicates the incremental series number and (I − 1/2) and (i + 1/2) refers as mia d incremental series number.

2.1 Modelling of Liquid Storage Tank

The finite element modeling for the liquid storage tank is defined. The analysis needs to be compatible with the fluid part of the storage tank which also accounts for the fluid–structure interaction. The tank is modeled with a solid element which is an eight noded linear brick element with reduced integration and hourglass control (C3D8R). The second part of the assembly is the fluid that is modeled with the solid element and the combined hourglass control, which smoothens the analysis as fluid is imparted to a higher level of distortion. The fluid element is refined with the powerful feature, i.e. Arbitrary Lagrangian and Eulerian (ALE). The tank taken in the analysis is flexible so that the inertial effect of the fluid media due to the ground motion can be measured. To extract result of higher accuracy, a mesh convergence is taken up, and convergence is reported at a mesh size of 0.05 m for the fluid media and 0.1 m for the tank elements.

To stimulate an Earthquake ground motion in a liquid storage tank earthquake time history in the form of acceleration time history is given and applied at the base of the tank. A single dynamic explicit step is defined for the earthquake motion, the value of period is taken differently for respective ground motion. While considering the effect of the union of two different media the need of an interaction property is necessary. A surface to surface contact is defined between the fluid and inner tank surface. The advantage of defining the surface to surface contact is that,it takes into the consideration of the sharp edges which develops an issue of geometry cumbersome that prolongs the computational time.

For the comparative study, the ground motion is applied in the base concerning the X, Y and Z axis. The explicit procedure involves the use of many small-time increments. It uses the central difference operator which is conditionally stable. The value of stable time increment is given by Eq. 4. The presence of high-frequency oscillations increases the stable time increment thus, to mitigate the effect of these oscillations of minuscule order of damping is added into the operator.

$$\Delta t \leq \frac{2}{\omega_{max}}\left(\sqrt{1+\xi^2}-\xi\right) \tag{4}$$

During the analysis progress, a global estimation program in the explicit module finds out the maximum frequency which is the maximum of the whole system. In the nonlinear problems, the frequency of the system is subjected to changes which in turn changes the stability limit.

The modeling of the fluid media is taken care by the aid of Mie-Gruneisen equation of state in Abaqus explicit module. The equation of state provides a media characteristic of hydrodynamics with respect of volumetric strength. Its ability to calculate the pressure as a function of the mass density and the specific energy makes it a robust tool in dealing with the fluid media.

The Mie-Gruneisen Equation of State represented in first-order form of polynomial Eq. (5).

$$p - p_H = \Gamma_\rho (E_m - E_H) \tag{5}$$

Here, p_H and E_H are Hugoniot pressure and specific energy as a function of density, whereas Γ is known as Gruneisen ratio and is equals to the value given in Eq. (6)

$$\Gamma = \Gamma_o \frac{\rho_0}{\rho} \tag{6}$$

The above equation is then simplified into the Eq. (7)

$$p = p_H\left(1 - \frac{\Gamma_o \eta}{2}\right) + \Gamma_o \rho_0 E_m \tag{7}$$

To fit the Hugoniot equation in a linear form, a common Hugoniot equation then becomes as Eq. (8)

$$p_H = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2} \tag{8}$$

In the Eq. (9), c_0 and s represents the single order relationship between the linear shock velocity, U_s and particle velocity, U_p in the form of

$$U_s = c_0 + sU_p \tag{9}$$

By considering the above equation of state $U_s - U_p$ Hugoniot form is presented in the Eq. (10) given below.

$$p_H = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2}\left(1 - \frac{\Gamma_o \eta}{2}\right) + \Gamma_o \rho_0 E_m \tag{10}$$

The ALE is an adaptive meshing tool which gives the advantage to maintain the integrity of the original mesh. A result of the unaffected topology of the fluid media is observed which is allowed due to the independent motion of the mesh nodes, therefore even the during the high scale deformation, the analysis doesn't lose its stability and a steady flow of analysis is maintained. The fluid mass is given the adaptive mesh properties in the present problems. The movement of the mesh covers the same domain of material in the direction which is normal to the motion of the material boundary. Adaptive meshing proved to be pragmatic in this analysis as the fluid media is expected to be deformed severely which leads to termination of the simulations. Not only the ALE posses the property to solve the dramatic change in the material mesh but also it provides results of faster and higher accuracy as compared to the pure Lagrangian approach. Due to the plethora amount of the element distortion and convolution of the mesh, which induces a loss in computational precision and augments the size of the stable time step.

3 Numerical Study

For the present study, a flexible rectangular tank is taken with ground support. To study the vertical effect of earthquake component in the liquid storage tank, different earthquakes are taken into the consideration with different peak ground acceleration (PGA) values. The tank is taken as a steel tank with a thickness of 0.2 m and with a cross-sectional size of 10 m by 10 m. The steel structure is provided with 3% damping. The height of the fluid stored in the tank is of 7.5 m. The sundry properties of the tank and fluid media are given in theTables 1 and 2.

To develop a lucid conclusive study for the effects of vertical components of earthquakes, various response quantities are extracted. The response of the liquid storage tank is represented with respect to the period of the earthquakes. The paramount study of the interaction between the fluid and tank structure surface with first only the bi-directional horizontal components and then after with tri-directional interactions

Table 1 Material properties for the tank and Fluid media

STEEL	FLUID
Modulus of Elasticity, $E_s = 200$ GPa	*Density,* $\rho_w = 983.204$ Kg/m3
Density, $\rho_s = 7900$ Kg/m^3	*Equation of state*: $c_0 = 1450$, $s = 0$, $\gamma_0 = 0$
Poisson's ratio, $\upsilon = 0.3$	*Dynamic Viscosity* = 0.001 N-sec/m^2

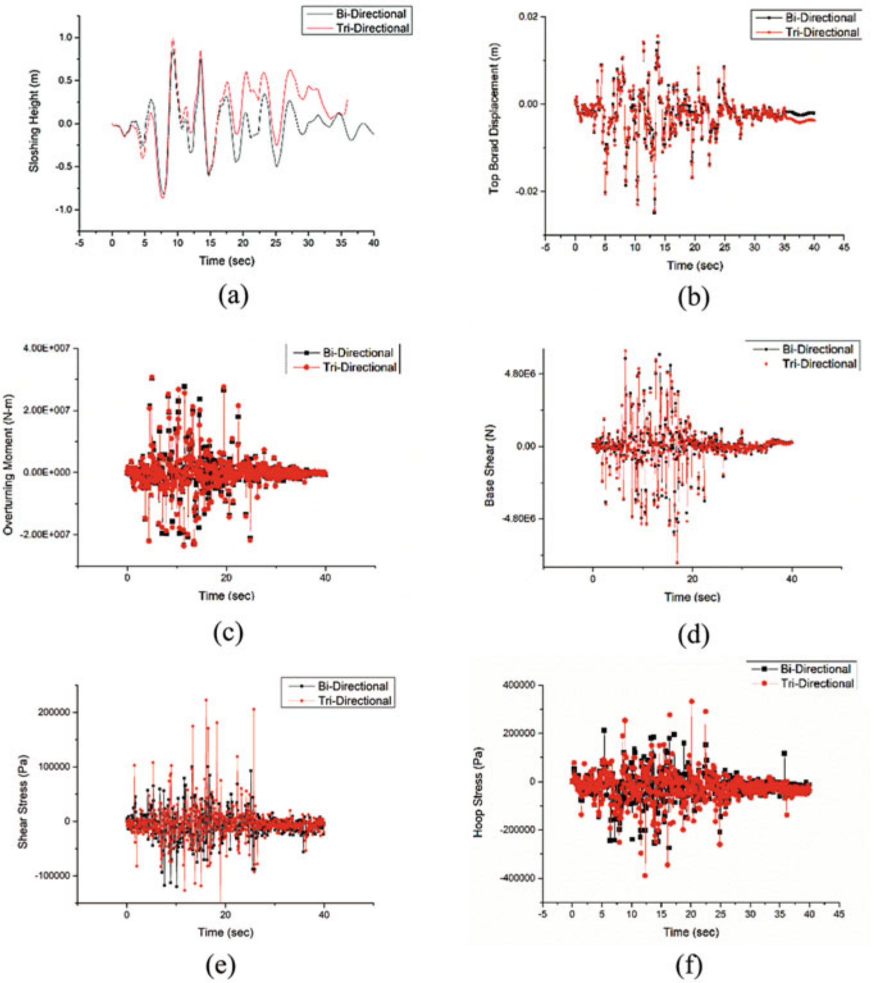
Table 2 Earthquake record data taken for the analysis

Name of earthquakes	Recording station	Time interval (s)	PGA in x-direction (g)	PGA in y-direction (g)	PGA in z-direction (g)
Bhuj Earthquake (2001)	IIT-R	35	0.69	0.64	0.6
Tabas Earthquake (1978)	Iran	40	0.41	0.35	0.32
Taiwan Earthquake (1986)	Hualien	35	0.195	0.2	0.17

along with vertical components of various ground motions are taken. The impact of material flexibility in tank walls in the analysis of the present study is included while extracting the responses. The responses which are taken for the comparative study are the top board displacement of the tank wall, sloshing height of the fluid media, base shear, overturning moment of the liquid storage tank, shear stress and hoop stress in the tank wall. The development of the time histories of the various response quantities are first extracted and are then are put are in a juxtaposition. The sloshing height of the fluid is extracted at the corner of the tanks. The top board displacement of the tank wall is computed at the right side of the wall in the y-direction. Various stresses which are shear stress and hoop stresses are calculated for the tank wall. To get a profound detail of the tank overall stability and behaviour under the given interactions both the shear force and overturning moment of the tank at the base are provided.

It can be observed from the Fig. 1a for the bi-directional interaction alone that motion of the fluid mass tends to increase first as the time history of the earthquake is proceed. The motion of the sloshing height in the tri-directional scenario can be observed somewhat same, but as the analysis is progressed towards the ends, it can be seen that magnitude of the sloshing height is more than that of the bi-directional interaction.

The top board displacement is discovered for the Bhuj earthquake in Fig. 1b to fold the relative pattern in both the bi-directional and tri-direction interaction.it can be seen from the graph that the peak values here is by the tri-directional interaction of the ground motion. In the case of the tank structural stability, the time history of



(a) (b) (c) (d) (e) (f)

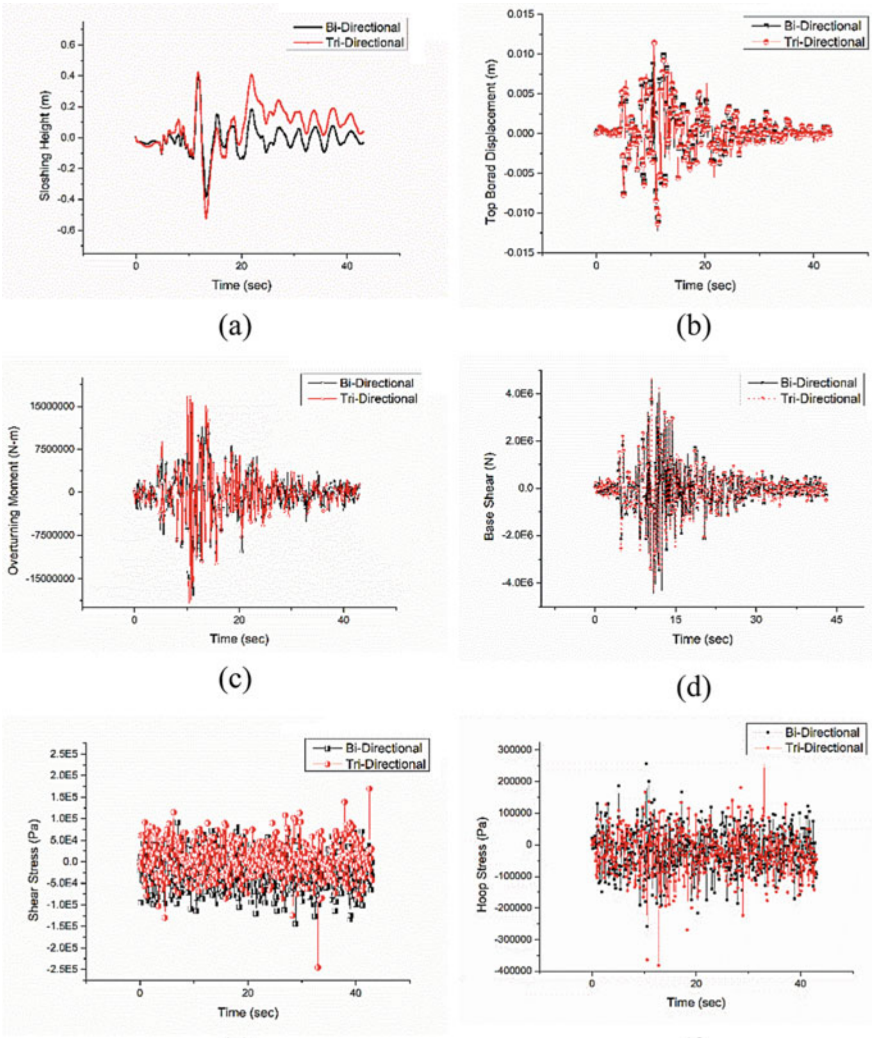
Fig. 1 Various response quantities for the Bhuj Earthquake, **a** *sloshing height* **b** *top board displacement* **c** *overturning moment* **d** *base shear* **e** *shear stress* and **f** *hoop stress*

the overturning moment and base shear shows the peak values at the relatively the nascent stage of the time history. A lucid bifurcation can be marked between the peak values of the tri-directional and bi-directional earthquake interaction. The evidence in the literature review supports the response quantities for the present study are in synchronization, as the vertical component of the ground motion has weakened the stable phase of the liquid storage tank. By examining the stresses time history of the tank wall, it can be clearly justified that due the third component of the ground motion a hike in the sloshing height is observed which in turn impact the tank walls and that results in augmentation in the shear stress and hoop stress as described by the Fig. 1e, f.

For the case of the Tabas Earthquake, one of the highlighted properties is that the PGA level of the ground motion is considerably lower than that of the Bhuj ground motion. The response quantities seem to be dormant by a change in PGA level and display the same trend as that of the higher PGA ground motion. The various response quantities show an unbalance in the peak values. The absolute peak values of the Tri-directional interaction seem to be the dominant one. Although the tri-directional interaction leads the peak values at almost every increment, in case of the top board displacement of the tank wall the difference is small. The effect of the light vertical contribution in the tri-directional response can be seen for the overturning and base shear time history plot. The peak values the stability variables, i.e., overturning moment, and base shear are achieved between the initial and mid-interval of their time history as shown in Fig. 2c, d. The peak values of these response quantities are observed at the somewhat same location as that of the sloshing height.it can be evidently because of the unbalanced inertial force that is generated by the sloshing mass. Thus, to mitigate this unbalanced mass an energy ameliorating obstruction need are demanded. While determining the shear and hoop stresses in the tank wall, the response displayed peak values at a prolonged time. The values are found near the latter stage of the time history. The peak values are of order twice of that are observed at the initial passage of the time. A significant change in time history values is seen before the half interval of the hoop stress time history as given Fig. 2e, f. The response graph reaches a maximum low value. The order of the difference between both interactions is seen of the highest order here.

The results obtained by the Taiwan ground motion holds the trends, as observed in the above couple of ground motion. In Fig. 3a the time history response of the sloshing in the fluid media is plotted. The maximum value in the sloshing height is marked by the tridirectional interaction. The PGA level taken in this ground motion analysis is the lowest. The value of the sloshing height in the initial stage of the program has developed a crescent look in the tri-directional part. After that on somewhat every peak developed in the response are shadowed by the tri-directional response. The value uncovered in the top board displacement of the tank wall seems to be the quite small it may be because of the elastic strength of the steel. The top board displacement is achieving its zenith value at the nearly same position when the sloshing in the tank is at its highest coordinate. The values in the stability parameters follow the quite a similar path as shown in the Fig. 3c, d. The increase in these values suggests that to get a realistic value while describing the behavior of the liquid storage tank under earthquake ground motion, we cannot ignore the vertical component. The nature of the stresses in the tank due to the unbalanced mass of the fluid media is a complex phenomenon driving from the combined effects of the fluid–structure interaction and the inertial behavior of the fluid media. Here also the maximum values are achieved at the relatively the same time interval as in the various time responses reported for this ground motion.

From Table 3, the maximum absolute values of the various output extracted are shown. For the present study is concluded with the help of the three different earthquakes having different peak ground acceleration magnitude. To comprehend the change in the output values for the various interaction for the ground motion under



(a) (b) (c) (d) (e) (f)

Fig. 2 Various Response Quantities for the Tabas Earthquake, **a** sloshing height **b** top board displacement **c** Overturning moment **d** base shear **e** shear stress and **f** hoop stress

consideration are shown in Table 4. It can be seen that a considerable amount of the imbalance is present between the values of bi-directional and tri-directional interaction for the various values responses.

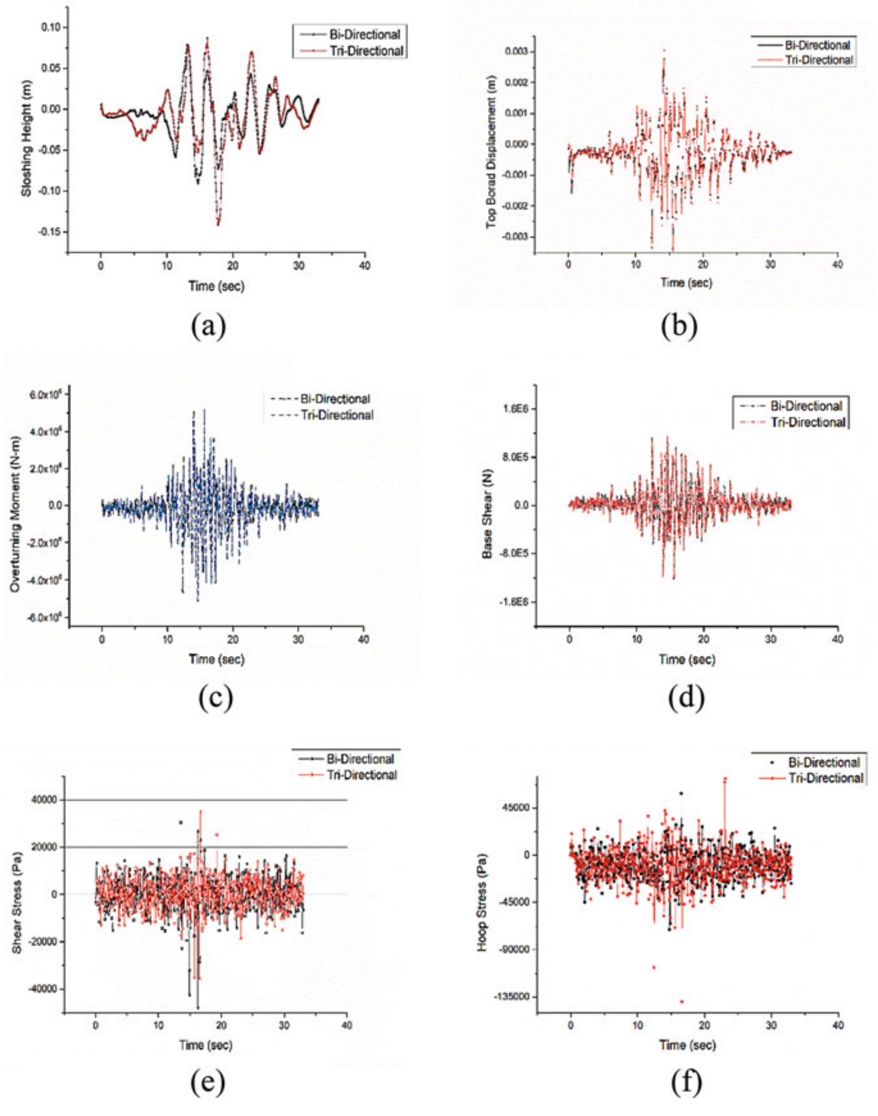


Fig. 3 Various Response Quantities for the Taiwan Earthquake, **a** *sloshing height* **b** *top board displacement* **c** *overturning moment* **d** *base shear* **e** *shear stress* and **f** *hoop stress*

4 Conclusions

The behavior of the liquid storage tank resting on the ground is taken up for the analysis in a finite element modeling software ABAQUS. A rectangular tank having both sides of equal length is taken as a model with fluid capacity at 75 percent. The nonlinear time history analysis is done for the conclusive remarks for the impact of

Table 3 Peak values of the various quantities taken under study represented along with their respective ground motion

Name of Earthquakes	Type of interaction	Sloshing height (m)	Top board displacement (m)	Overturning moment (N-m)	Base shear (N)	Shear stress (Pa)	Hoop stress (Pa)
Bhuj Earthquake (2001)	Bi-Direction	0.853	0.014	1.61e07	6.09e06	1.00e05	2.080e05
	Tri-Direction	0.980	0.0159	1.81e07	6.35e06	2.25 e05	3.37e05
Tabas Earthquake (1978)	Bi-Direction	0.36	0.011	1.62e07	4.40e06	8.084e4	2.66e05
	Tri-Direction	0.41	0.010	1.75e07	4.71e06	1.680e5	3.26e05
Taiwan Earthquake (1986)	Bi-Direction	0.083	0.0028	4.92e06	1.05e06	2.55e04	6.24e04
	Tri-Direction	0.090	0.0030	5.26e06	1.75e06	3.65e4	7.78e4

Table 4 Percentage change recorded between the tri-directional and bi-directional interactions for the various extracted response outputs

Name of earthquakes	Sloshing height	Top board displacement	Overturning moment	Base shear	Hoop stress
Bhuj Earthquake	14.9	13.6	12.4	4.3	62.0
Tabas Earthquake	13.9	9.1	8.0	7.0	22.6
Taiwan Earthquake	8.4	7.1	6.9	66.7	24.7

the vertical acceleration in the contribution for the various structural failures during the ground motions. Three types of ground motion are taken up, with different PGA values. The following conclusions can be drawn from the numerical study:

1. The pattern of the tri-directional ground motion follows bi-directional interaction, but in every case, the peak values of tri-directional interaction seem to surpass that of the bi-directional interaction.
2. The small-scale change can be seen in the response case of top board displacement.
3. The sloshing response seems to hold the most changed response in graphical form for the tri-directional interaction than that of the bidirectional interaction.
4. The values of the peak are generally developing when the height of the sloshing fluid is at maximum. Thus, it gives the physical sense of various stresses that are resulted due to the complex FSI and increase in the inertial force of fluid media during seismic activity.

5. The dramatic increase can be seen for the shear stress due to the tri-directional interaction case. The value shows to increase with higher PGA levels and lowers with lesser PGA levels. The hoop stress holds a relatively stable change in the values a maximum percentage change is reported for the Bhuj earthquake.

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