**Response Control of Base Isolated Liquid Storage Tank under Bi-directional Earthquakes**

**DOI 10.37153/2686-7974-2019-16-1152-1161**

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**ABSTRACT**

Failures of liquid storage tanks are observed during earthquakes. Thus, their protection has drawn the attention of researchers. In the present study, the behavior of the liquid storage tank is investigated under the action of a bi-directional earthquake and base isolation devices are implemented to control the responses of liquid storage tanks. A nonlinear time history analysis of the liquid storage tank under bi-directional ground motions is carried out using ABAQUS which uses Arbitrary Lagrangian-Eulerian (ALE) FEM for solving Fluid-structure interaction problem. Five base Isolators, four at the four corners of the tank and one in the middle, are provided to control the responses of the liquid storage tank. The parameters varied are the different ground motions and the angle of incidence of the earthquake with respect to the principal axis of the tank. The response parameters considered for investigation includes the sloshing height, the base shear, the overturning moment and the Von-Mises stress in the tank wall. The study shows that base isolation can adequately control the stresses developed in the tank but amplifies the sloshing wave greatly.

*Keywords: Sloshing; FEM; NTHA; Base Isolations; Angle of incident*

**1. INTRODUCTION**

The behavioral understanding of liquid storage tank (LST) in a seismic event possesses difficulty, due to the involvement of different complex interactions. This has posed a challenge to the earthquake community to understand its seismic behavior and several researches have been carried out in this regard. Further, because of its invariable requirement in the nuclear, petroleum, water supply, and chemical industries, the protection of such structures against seismic hazard has drawn considerable attention of researchers.

There exists a plethora of paradigms in which LSTs have failed in the event of an earthquake. Losses of huge magnitude were reported in the Valdivia earthquake, Chile (1960), Eureka earthquake, California, (1980), Sierra Madre earthquake, California (1991), Hokkaido earthquake, Japan (2003), Sumatra Earthquake, Indonesia (2004), Great East Japan earthquake, Japan (2011) and Central Mexico earthquake, Mexica (2017). Some of the common structural failures in seismic events were elephant foot buckling at the bottom of the tank, damage of the tank roof due to the sloshing of liquid, uplifting of the base and sliding off the bottom of the tank.

The LSTs resting on the ground and subjected to earthquakes retain the inertial property of the liquid mass stored in it. The mass of the fluid media splits into two masses, known as convective and impulsive masses. Convective mass is present at the top of the tank and is responsible for the sloshing of the liquid, while the impulsive mass remains close to the tank wall which is responsible for the major hydrodynamic pressure on the tank walls. When considering the wall flexibility, the convective mass holds different motion than that of the tank walls and the rest of the mass moves with the walls. The resultant response of these two mass quantities provides lateral pressure on the tank wall and the overturning moment on the foundations respectively. The high intensity of the overturning moment at the base of LSTs results in the high magnitude of the compressive stresses at the base. The large magnitude of the compressive stress, in turn, results in the buckling of the tank walls, critical loss of the piping system and upheaval of the base encouragement system of the tank.

The abstruse behavior of the liquid storage tank due to fluid structure interaction makes the analysis cumbersome. (Housner 1957) represented dynamically the hydrodynamic pressure created by the horizontal component of earthquakes and derived the simple methods in the form of equations. (Housner 1963) explained the dynamic behaviour of the tank with the help of simplified models for different types of the tanks i.e. Elevated tanks and tanks on the ground and concluded that a true description of the dynamic forces associated with the sloshing water was needed. (Wozniak and Mitchell 1978) presented the updated methods from the API 650, which assumed that the tank was infinitely rigid, and the roof and the wall of the tank moved in unison. Additional information was provided in the form of curves to facilitate the design calculations for sloshing height and the forces on the roof along with the hoop tension. (Liu 1981) presented a nonlinear finite element method which treated the structural behaviour of the tanks in conjunction with fluid, including the dynamics and buckling.(Haroun and Tayel 1985) studied the tank responses in both vertical and lateral excitations and found out the relative importance of the vertical component of the ground acceleration in the overall seismic behaviour of liquid storage tanks.(Veletsos et al. 1986) defined a practical procedure for finding out the various dynamic responses of a cylindrical liquid storage tanks for the action of the vertical component of the earthquake. The study also reported that soil-structure interaction could be a factor in the reduction of the hydrodynamic effects as it changes the natural frequency of the system.(Fischer and Seeber 1988) investigated the response of the cylindrical shell which was entirely filled up by an incompressible and inviscid fluid and was resting on the flexible foundation with a frequency dependent stiffness and damping. The approach also included, the fluid structure interaction and the soil structure interaction in the solution for finding the maximum dynamic pressure. (Tedesco et al. 1989) evaluated different analytical methods comprehensively for a circular cylindrical tank subjected to the horizontal earthquake motion. The evaluation procedure was further translated into a computer program. (Malhotra 1995) presented an approximate method for the analysis of the uplifting phenomena in the liquid storage tanks. The method showed that during the uplifting of the base, hoop stresses were of a higher order than that of the axial compressive stresses. (Shrimali and Jangid 2004) displayed the efficacy of the approximate method in establishing the effectiveness of the base isolation in the LST. (Cheng et al. 2017) examined the large isolation layer displacement during the earthquake motions for the sliding base Isolators and employed a displacement-limiting device while considering an arc displacement-limiting device.

The objectives of the present study are (i) to understand the behaviour of liquid storage tanks under bi-directional earthquake and (ii) to control the seismic responses of the tank by base isolation. A finite element method is used to consider the complete dynamic fluid structure interaction. A three-dimensional model of the liquid storage tank, liquid and the lead rubber bearing isolators are implemented in the ABAQUS software. The response analysis is performed under bi-directional earthquake having an angle of incidence with the principal direction of the tank.

**2.Theory**

The The behaviour of the liquid storage tank under the action of the seismic excitation involves non-linear analysis of the liquid-tank system. The sudden motion at the base of the tank develops the large inertial resistive stresses which gets further increased due to the hydrodynamic motion of the fluid stored inside the tank. As the fluid is dispersed due to the flexibility of the tank wall, the sloshing of the fluid media is augmented which further impacts the tank walls and pushes the overall behaviour of the tank towards the non-linearity. The non-linearity developed during the analysis is handled by ABAQUS with the aid of an explicit central-difference integration rule. The input of the diagonal mass matrix at the initial of the time step increment results from Equation (1).

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

where MNJ is the mass matrix, PJ is the load vector, and IJ is the force vector.

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

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

The equation of motion for the solution is integrated using the central difference integration rule as stated in Equations 2 and 3, where $\dot{u}$ and $\ddot{u}$ are the velocity and the acceleration values respectively. The superscript (*i*) indicates the incremental series number; (i-1/2) and (i+1/2) refer to mid incremental series numbers. The explicit procedure employs the use of several small-time increments. It takes the central difference operator which is by default conditionally stable. The stable time increment is calculated by Equation (4). Due to the presence of high-frequency oscillations, the stable time increment increases. A small level of damping is added into the operator for compensating the requirement of time increment.

$Δt\leq \frac{2}{ω\_{max}}\left(\sqrt{1+ξ^{2}}-ξ\right)$ (4)

During the analysis, 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. In the present study, the Mie-Gruneisen equation of state is opted. This equation of state holds the relationship between hydrodynamics and the volumetric strength. The calculation of the pressure as a couple of variables, namely, specific energy and mass density, provides a powerful and successful tool for modelling the fluid. The Mie-Gruneisen equation models the velocity of the particle and velocity of shock in Hugoniot form which is itself represented in a linear form as represented in Equation 5.

$U\_{s}=c\_{0}+sU\_{p}$. (5)

The final form of the equation of the state as a Hugoniot form is given in Equation 6

$p\_{H}=\frac{ρ\_{0}c\_{0}^{2}η}{\left(1-sη\right)^{2}}\left(1-\frac{Γ\_{o}η}{2}\right)+Γ\_{o}ρ\_{0}E\_{m}$. (6)

where $p\_{H}$ and $E\_{m}$ are Hugoniot pressure and specific energy respectively, as a function of density, whereas $Γ$ is known as Gruneisen ratio (Dassault Systèmes Simulia 2012).

The impulsive and convective equivalent weights of the accelerating liquid are calculated following the guidelines of (ACI 350 2007)

$ω\_{C}=\sqrt{(nπg/L)tanh\left((nπH\_{L}/L)\right)}$ (7)

Equation 7 provides the fundamental circular frequencies in the convective mode of the liquid inside the tank which is responsible for the sloshing phenomena, whereas, the impulsive frequency gives the stresses in the tank, which is produced due to the combined effect of fluid mass that stick to the wall of the tank and the self-weight of the tank. As the convective mode is not dependent on the motion of the tank, sloshing response is independent of the material property of the tank.

For controlled the responses in the liquid storage tank, the Lead-Rubber Bearing (LBR) is employed here. The paramount importance in LRB design is to make a distinct change in natural frequency of the structure so that accommodation of a new frequency can be taken which have a longer time period value. To provide an LRB with sound property different use of materials are employed. The LRB consists of alternating layers of different materials, namely, steel and rubber which provide the isolator with flexibility and simultaneously maintain a sound vertical stiffness. The isolator is equipped with a lead core at the center. The position of the lead core at the center provides additional damping and stiffness. LRB holds a linear elastic-plastic behavior and a good fatigue resistance. The ratio of the pre and post yield stiffness is taken as 10. The seismic energy is absorbed by the isolation device in the form of hysteresis loop (Datta 2010; Naeim and Kelly 2000).

***2.1 Finite Element Modelling details***

For FEM, the tank is considered as flexible and surface to surface interaction is deployed between the fluid and the wall surfaces. The tank is modelled by an eight-node linear brick element with a supplement of reduced integration and hourglass control which aids in expediting the solution. The fluid is also modeled by the same solid element with combined hourglass control wielding the stiffness-viscous weight factor of unity. To keep up with the deformation of large magnitude with the fluid media, different hourglass control is provided than tank media and an adaptive mesh control is given. Arbitrary Lagrangian and Eulerian (ALE) approach is used which maintains the mesh and results in faster and higher accuracy outputs, as compared to the pure Lagrangian approach.

The isolation behavior is developed by the two nodded connector elements. The connectors are used with different types of physical properties. They include damping, lateral flexibility and the nonlinear kinematic hardening behavior of the LRB. A linear coupled elastic behavior can be simulated for the spring matrix using Equation 8.

 (8)

where *Fi* is the force, uj is the motion of *jth* node. Similarly, development of the damping force is defined using Equation 9.

 (9)

where *Fi* is force in the *ith*component of relative motion, *vj* is velocity in the *jth* component and *Cij*is thecoupling between *ith* and *jth*components. For nonlinear kinematic hardening behavior, the connector is given the nonlinear kinematic hardening property. Because of this property, center of the yield surface can translate into the force space. The yield surface is defined by Equation 10, where *F0* is the yield value and *P(f-α)* is potential with respect to back force *α.*(Dassault Systèmes Simulia Corp. 2012)*.*

 (10)

**3. Numerical study**

To investigate the behavior of the liquid storage tanks under the action of bidirectional earthquake and the control responses of the tank by base isolation, a square tank of side 10m is taken as an illustrative example. The thickness of the tank is 0.7m and the height is taken the same as that of the sides. The water height is taken as 8m. The material damping is taken as 0.05. Other relevant properties used for the analysis are shown in Table 1. A couple of earthquake time history analyses are carried out for studying the non-linearity effect of the concrete material of tank. To develop the understanding of the natural behavior of the nonlinearity in the tank an explicit step procedure is selected with respective time period of the earthquake history. A mess convergence study is carried out to find the optimum mesh size for accurate results. The mess convergence study showed the constant values with fluid mesh size being smaller than that of the tank element.

An arrangement of five base isolation devices is chosen such that 4 isolators are placed at all the four corners of the base and one is placed at the center of the tank base. For the employment of base isolation, two different connector elements, namely, cartesian and align are used. The application of cartesian type connector system allows the fine translation motion to the structure along the all three axes, whereas by including the align connector the rotational motion of the isolator is hindered. The isolation period for the structure is taken as 1.28sec which is almost the four times the time period of the impulsive mode. According to the design time period of the base isolation, various properties of the LRB is fixed, namely, the initial stiffness as 7210 KN/m in both the lateral and transverse motion, the vertical stiffness as rigid, post-yield stiffness as 7566.374KN/m and the equivalent stiffness as 91670KN/m.

Table 1. Material Properties for Tank and Fluid

|  |  |
| --- | --- |
| **CONRETE** | **WATER** |
| Modulus of Elasticity,Es = 24.86 GPa | Density, ρw=983.204Kg/m3 |
| Density, ρs=2450Kg/m3 | Equation of state: c0= 1450, s =0, γ0=0 |
| Poisson’s ratio, υ=0.17 | Dynamic Viscosity = 0.001 N-sec/m2 |

For the uncontrolled response analysis, the earthquake time history is applied at the base of the tank, whereas for the case of the controlled responses, the earthquake time history is applied at the base of the isolators. The details of the earthquake time histories are shown in Table 2. The response quantities of interest include the base shear, the overturning moment, the Von-Mises stresses at the base of the tank and the sloshing height. As the study is concerned with the bi-directional interaction along with different angles of incidence, sloshing heights are captured at the extreme outward directions of the positive lateral and transverse position of the fluid media.

Table 2. Earthquake Data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name of Earthquakes** | **Recording Station** | **Time Interval (sec)** | **PGA in x-direction** | **PGA in y-direction** |
| Imperial Valley (1940) | EL Centro | 30 | 0.35g | 0.22g |
| Colima (2003) | Mexico | 40 | 0.41g | 0.17g |

The natural frequency for different modes is shown in Table 3. The time histories of sloshing wave heights are shown in Figure 1 for two angles of incidences, namely, zero degree (aligned in the direction of one of the sides of the tank) and 15 degrees (to the line parallel to one of the sides of the tank).

Table 3. Natural Frequency for Different Modes

|  |  |
| --- | --- |
| **Type of mode** | **Frequency (Hz)** |
| Impulsive | 3.125 |
| Convective | 0.278 |

It is seen from the Figure 1 that there could be a significant change in the time history of sloshing wave height with the change in the angle of the incidence of earthquake, as observed for the Colima earthquake. However, there is no significant change in the time histories of sloshing wave height with the change in the angle of incidence of earthquake for the EL-Centro earthquake. Thus, the effect of the angle of incidence on the sloshing height depends upon the nature of earthquake. Figure 2 shows the time histories of the overturning moment for the two angles of incidence of earthquake. It is seen from the Figure 2 that for both earthquakes, the angle of incidence of earthquake influences the time histories of overturning moment. The reason for this may be attributed to the bidirectional interaction of earthquakes, which provides different forces on the walls of the tank as the angle of incidence of earthquakes is changed.

From the Table 4 and 5 it can be inferred that angle of incident can change the magnitude of responses. Angle of incidence seems to have the same effect for the El-Centro earthquake for both the controlled and uncontrolled responses and there is an increase of twenty percent in the Von-Mises stress for the uncontrolled responses. Tables 4 and 5 are providing absolute maximum value in respective output. While controlling response showed a maximum reduction of five percent in the overturning moment for sixty-degree orientation. All the responses in the Colima earthquake displayed a similar pattern of rise and fall in both controlled and uncontrolled analyses. However, sloshing height displayed a tremendous gain of seven times that of the initial orientation. Negligible deviation in both controlled and uncontrolled value of Von-mises stress can be seen with time history pattern almost resembling same as that of in both controlled and uncontrolled cases.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 1. Sloshing Responses for (a) Colima Earthquake (b) EL-Centro Earthquake

|  |  |
| --- | --- |
|  (a) | (b) |

Figure 2. Overturning Moment for (a) Colima Earthquake (b) EL-Centro Earthquake

|  |  |
| --- | --- |
| (a) | (b) |

Figure 3. Von-Mises Stress for (a) Colima Earthquake (b) EL-Centro Earthquake

Figure 3 shows the time histories of the Von-Mises stress for the two angles of incidences of the earthquake. Here again, it is seen that the angle of incidence of earthquake has some effect on the time histories of stresses developed in the tank. The same reason as mentioned above may be attributed to this effect. Figure 4 shows the time histories of the base shear for the two angles of incidences of the earthquake.

|  |  |
| --- | --- |
|  (a) |  (b) |

Figure 4. Base Shear for (a) Colima Earthquake (b) EL-Centro Earthquake.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 5. Hysteresis Graph For (a) Colima Earthquake (b) EL-Centro Earthquake.

Table 4. Comparison Between the Uncontrolled and Controlled Responses of EL-Centro Earthquake.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **EQ.****NAME** | **BASE ISO-LATION** | **ANGLE OF INCIDENCE** | **WAVE HT (m)** | **OVERTURING MONENT****(MN-m)** | **BASE SHEAR****(KN)** | **Mises** **(KPa)** |
| **X** | **Y** |
| El Centro | NO | 0 | 0.25 | 0.39 | 15.1 | 5450 | 2150 |
| 15 | 0.39 | 0.36 | 15.0 | 5270 | 2340 |
| 30 | 0.52 | 0.31 | 14.5 | 5380 | 2490 |
| 45 | 0.60 | 0.26 | 15.3 | 5560 | 2550 |
| 60 | 0.64 | 0.25 | 14.9 | 5660 | 2520 |
| 75 | 0.64 | 0.22 | 15.4 | 5520 | 2530 |
|  |  |  |  |  |  |  |  |
| El Centro | YES | 0 | 0.34 | 0.50 | 11.2 | 2570 | 1870 |
| 15 | 0.52 | 0.46 | 10.8 | 2580 | 2190 |
| 30 | 0.70 | 0.45 | 11.2 | 2580 | 2190 |
| 45 | 0.82 | 0.42 | 10.7 | 2580 | 2080 |
| 60 | 0.90 | 0.37 | 11.0 | 2580 | 2230 |
| 75 | 0.92 | 0.32 | 10.7 | 2580 | 2210 |

Table 5. Comparison Between the Uncontrolled and Controlled Responses of Colima Earthquake.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **EQ. NAME** | **BASE ISOLATION** | **ANGLE OF INCIDENCE** | **WAVE HT (m)** | **OVERTURING MONENT****(MN-m)** | **BASE SHEAR****(KN)** | **Mises (KPa)** |
| **X** | **Y** |
| Colima | NO | 0 | 0.23 | 0.89 | 44.8 | 3250 | 1000 |
| 15 | 0.27 | 0.64 | 46.5 | 3320 | 1000 |
| 30 | 0.43 | 0.55 | 46.7 | 3340 | 1010 |
| 45 | 0.63 | 0.45 | 46.3 | 3520 | 1010 |
| 60 | 0.76 | 0.31 | 46.8 | 3440 | 995 |
| 75 | 0.93 | 0.13 | 47.2 | 3620 | 994 |
|  |  |  |  |  |  |  |  |
| Colima | YES | 0 | 0.18 | 1.48 | 28.5 | 1620 | 722 |
| 15 | 0.34 | 1.37 | 29.0 | 1650 | 739 |
| 30 | 0.56 | 1.13 | 28.9 | 1630 | 748 |
| 45 | 0.94 | 0.82 | 37.3 | 1640 | 761 |
| 60 | 1.18 | 0.45 | 29.0 | 1640 | 739 |
| 75 | 1.54 | 0.29 | 37.3 | 1640 | 776 |

The effect of angle of incidence on the time histories of base shear is relatively less as compared to that for the von-mises stress and the overturning moment. Figure 5 shows the hysteresis loops formed during the inelastic excursion of the Isolators. The areas of the loops indicate that considerable seismic energy is dissipated in the Isolators. This is indicative of effective control of responses of the liquid storage tank by way of base isolation. The controlled and uncontrolled responses are compared in Tables 4 and 5 for different earthquakes and different angles of incidence. It is clearly seen from the Table 6 that sloshing height is increased, while other response quantities are decreased due to base isolation.

Table 6. Percentage Change with Respect to Uncontrolled Responses of Earthquakes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **EQ. NAME** | **ANGLE OF INCIDENCE** | **WAVE HT (m)** | **OVERTURING MONENT****(MN-m)** | **BASE SHEAR****(KN)** | **Mises (KPa)** |
| **X** | **Y** |
| El-Centro | 0 | 39% | 28% | -26% | -53% | -13% |
| 15 | 33% | 27% | -28% | -51% | -6% |
| 30 | 36% | 44% | -23% | -52% | -12% |
| 45 | 36% | 60% | -30% | -54% | -18% |
| 60 | 40% | 48% | -26% | -54% | -11% |
| 75 | 45% | 46% | -30% | -53% | -13% |
|  |  |  |  |  |  |  |
| Colima | 0 | -19% | 66% | -36% | -50% | -28% |
| 15 | 28% | 113% | -38% | -50% | -26% |
| 30 | 29% | 106% | -38% | -51% | -26% |
| 45 | 50% | 82% | -19% | -53% | -25% |
| 60 | 55% | 46% | -38% | -52% | -26% |
| 75 | 65% | 114% | -21% | -55% | -22% |

Further, it is seen from the Table 5 that the angle of incidence of earthquake has a significant effect on the maximum value of the sloshing height; the maximum values of other response quantities are not significantly affected. Table 5 shows the percentage control of the response quantities due to base isolation. While the sloshing height is amplified by as much as one hundred percent depending upon the angle of incidence of the earthquake, there is a significant reduction in other response quantities. The reduction in base shear is maximum and may be of the order of fifty percent. The reduction in the overturning moment is of the order of twenty to forty percent, while that of the von mises stress is of the order of fifteen to twenty percent. Note that the angle of incidence of earthquake does not have significant influence on the control of the response

**4. Conclusions**

The uncontrolled and controlled response behaviors of a base isolated liquid storage tank under the action of bi-directional earthquakes are investigated. The liquid storage tank filled with liquid inside is modeled using eight nodded brick elements. The isolators are modeled by connector elements available in ABAQUS software. The responses are obtained for two earthquake records, namely, those of EL-Centro and Mexico. The angle of incidence of the earthquakes with respect to the principal direction of the tank is varied in order to investigate its effect on the responses. The response quantities of interest include the sloshing wave height, the base shear, the overturning moment at the base and the maximum von-mises stress. The results of the specific numerical study lead to the following conclusions:

1. The angle of incidence of earthquake has significant influence on both uncontrolled and controlled maximum sloshing wave heights; it marginally influences other response quantities.

2. Considerable dissipation of seismic energy takes place in the Isolators leading to a good control of stresses developed in the tank.

3. Because of base isolation, the sloshing wave height is amplified by as much as hundred percent.

4. Out of the other response quantities, the base shear is better controlled, of the order of twenty to thirty percent; the overturning moment is controlled by about twenty to forty percent and the maximum von-mises stress is controlled by about fifteen to twenty percent.

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