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# SEISMIC ANALYSIS OF BASE-ISOLATED CYLINDRICAL LIQUID STORAGE TANK USING COUPLED ACOUSTIC-STRUCTURAL INTERACTION

**Aruna Rawat[1], Vasant Matsagar[2], and A.K. Nagpal[3]**

[1] Research Scholar, Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khaus, New Delhi – 110 016, India
e-mail: augupta2001@gmail.com

[2] Associate Professor Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khaus, New Delhi – 110 016, India

[3] Dogra Professor, Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi - 110 016, India.

**Keywords:** Base isolation, Base shear, Coupled acoustic-structure, Finite element, Liquid storage tank, Seismic analysis, Sloshing.

**Abstract** *Seismic analysis of three-dimensional (3-D) ground-supported base-isolated cylindrical liquid storage tank is investigated using coupled acoustic-structural interaction approach. In this approach of finite element (FE) method the contained liquid in tank is modeled with acoustic elements, having only pressure degree-of-freedom. By using the present approach the impulsive and convective or sloshing components acting on the tank can be evaluated separately by using the appropriate boundary conditions on the top of free liquid surface. The study is performed for two base isolation systems, elastomeric bearing and sliding system, which are modeled as non-linear connectors in the present study. A parametric study is performed to study the effectiveness of the proposed analysis method for broad and slender base-isolated tanks. The sloshing displacement and base shear time history responses are evaluated for 3-D tanks subjected to uni-directional earthquake ground motions. The FE time history responses are compared with the non-isolated 3-D tanks and it is found that the impulsive component of base shear has reduced more as compared to convective component of base shear. It is also seen that sloshing displacement was unaffected by the application of both the isolation systems.*

# 1 INTRODUCTION

Structures which are in contact with fluids exhibit a different behavior under seismic loads from other structures. The seismically induced motion of the structure causes dynamic pressure in the fluid, which in turn act upon the structure and hence modifies its dynamic response. This complex fluid-structure interaction (FSI) problem which arises not only for liquid storage tanks but also for large water reservoir and their containing structures as shown in Figure 1.

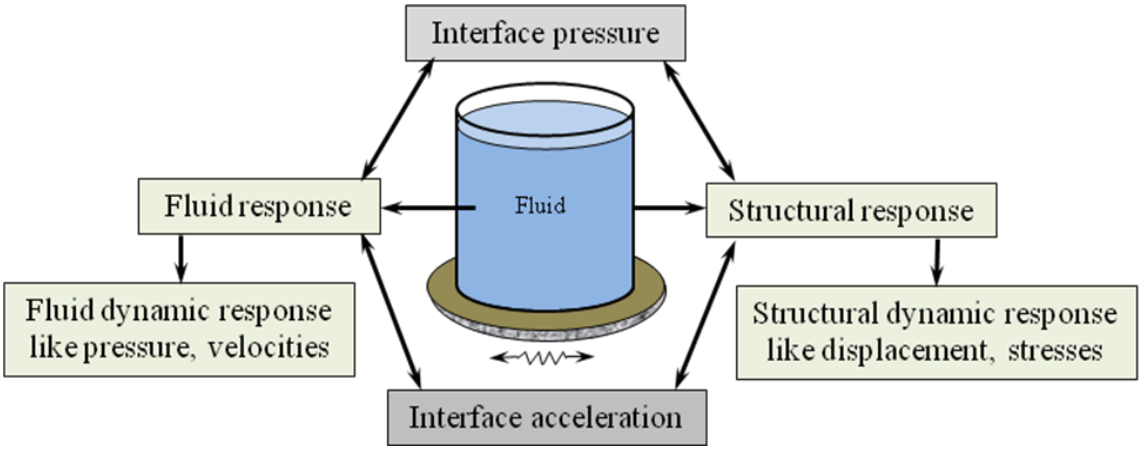


Figure 1 Fluid-structure interaction (FSI) problem.

Liquid storage tanks are the lifeline structures used for storage of various liquids, for example storage of water for drinking, fire-fighting system, industries, nuclear reactors. Failure of these liquid storage tanks were reported in past earthquakes events in the number of forms such as elephant foot buckling, diamond-shaped buckling, sliding of the base, uplifting of base, damage to the roof and the top of the tank wall caused by sloshing and failure of piping systems.

The protection of liquid storage tanks against the possible hazard of earthquakes is the major concern of the present design strategies. Over the three decades the development in the field of seismic control devices has reduced the failure of structure or the risk of damage in structures. Base isolation system has being extensively used to improve the seismic performance of the structures. This is achieved by introducing base isolation system between the foundation and the tank which causes the decoupling of the tank from the damages of earthquake ground motions. The purpose of using base isolation system is to lengthen the fundamental time period of the tank beyond the energy containing periods of earthquake ground motions.

Several researchers have studied base-isolated liquid storage using analytical, experimental and numerical methods. Chalhoub and Kelly [1] carried out several shake table tests on fixed base and base-isolated tanks using elastomeric bearings and observed the reduction in dynamic response but slight increase in the sloshing displacement. Bo and Jia-xiang [2] analyzed the ground-supported base-isolated liquid storage tank using lead rubber bearing (N-Z system) by finite element method. Kim and Lee [3] carried out pseudodynamic test on cylindrical liquid storage tank supported on laminated rubber bearings (LRB). Malhotra [4, 5] proposed a new method for base-isolated liquid storage tank in which the wall of the tank was supported over a flexible rubber bearing subjected to uni-directional and bi-directional components of earthquake. Kim et al. [6] numerically analyzed the three-dimensional (3-D) soil-structure-fluid interaction for base-isolated liquid storage tanks. Shrimali and Jangid [7] used three lumped mass model for the seismic response of tank with pure-friction (P-F) sliding system under bi-directional ground excitation. Shrimali and Jangid [8] performed a comparative study of various isolation systems for the liquid storage tanks. Cho et al. [9] analyzed the base-isolated liquid storage tank considering the soil-interaction effect using a coupling method that combines the finite element and boundary element methods. Jadhav and Jangid [10, 11] carried out the study on various parameters such as aspect ratio of tank, the period of isolation and the damping of isolation bearings on base-isolated tank. Panchal and Jangid [12, 13] used FPS and variable friction pendulum (VFPI) system for base isolation of liquid storage tank under uni-directional earthquake ground motion. Emre and Eren [14] carried out a parametric study of base-isolated ground supported tanks using curved surface sliding bearings. Christovasilis and Whittaker [15] used mechanical analog and finite element methods, for studying the behavior of isolated liquefied natural gas (LNG) tanks. Calugaru and Mahin [16] conducted experimental and analytical studies on isolated and fixed base liquid storage tanks mounted on triple pendulum system. Shekari et al. [17] investigated the effects of base isolation on the seismic response of cylindrical vertical flexible liquid storage tanks subjected to horizontal seismic ground motion considering the coupled boundary element-fluid element (BE-FE) method. Soni et al. [18] used double variable frequency pendulum isolator (DVFPI) for isolation of liquid storage tank under uni-directional earthquake using three lumped mass model. Ruifu et al. [19] studied the seismic response of an isolated vertical, cylindrical liquefied natural gas (LNG) tank by multiple friction pendulum system (MFPS). Fallahian et al. [20] carried out an analytical study of liquid storage mounted on double concave friction pendulum (DCFP) isolation system. In the present work the seismic analyses of 3-D ground-supported base-isolated cylindrical liquid storage tank is analyzed using coupled acoustic-structural approach of FE method. By the present FE model the effect of impulsive and convective components can be calculated separately.

The objectives of the present study are (i) to compare the sloshing and base shear response of base-isolated cylindrical liquid storage tank with non-isolated 3-D finite element tank subjected to uni-directional earthquake ground motion, (ii) to study the 3-D liquid storage tank isolated using elastomeric bearing LRB and sliding bearing FPS, and (iii) to study seismic response of the tanks with two different aspect ratios, height of liquid to radius of the tank.

## 2 NUMERICAL MODELING OF BASE-ISOLATED LIQUID STORAGE TANK

Many researchers have modeled fluid with acoustic elements in finite (FE) analyses. Morand and Ohyan [21], Everstine [22], Virella et al. [23] investigated the FSI problems using acoustic elements. In the present study, coupled acoustic-structure approach of FE method is used for the seismic analysis of base-isolated tank. In this approach the liquid content in the tank is modeled using an acoustic element AC3D8R, eight-node 3-D continuum element with reduced integration and hourglass control used for acoustic wave propagation. The tank wall are modeled with shell S4R and S3R elements, four-node quadrilateral and triangular 3-D element with reduced integration and hourglass control, respectively as shown in Figure 2. The base isolation system is modeled using connectors available in Abaqus finite element software [24], which act in horizontal direction. Connectors allow the connection between two points in an assembly or between a point in an assembly and ground. The base isolation system parameters are assigned to connectors.

In the present study boundary impedance interaction is defined at the free surface of acoustic medium to model the sloshing behavior considering the linearized wave condition. For the impulsive component of the liquid response, the boundary condition at free surface of liquid is to be replaced by zero pressure, $p = 0$ at $z = H_L$. The interaction between the tank walls and acoustic liquid elements is defined using a surface-based tie constraint [24].

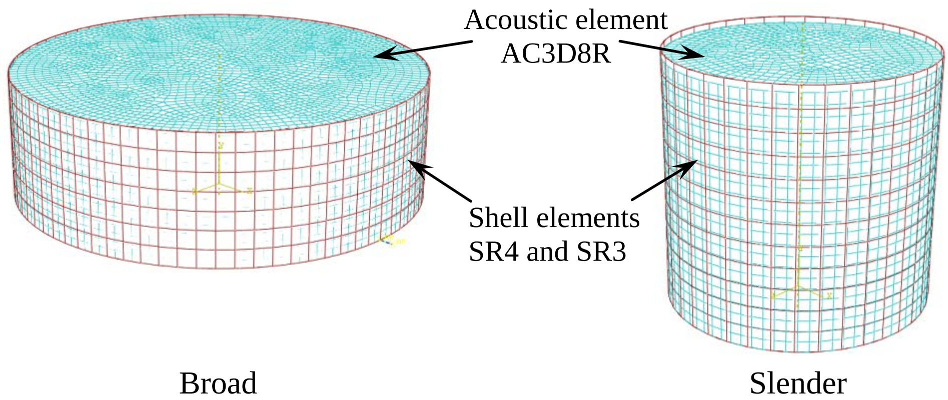


Figure 2 3-D FE model of base-isolated liquid storage tank.

## 3 NUMERICAL STUDY

In the present study, 3-D FE ground-supported flexible base-isolated tank are investigated under uni-directional earthquake ground motions. The two aspect ratios, $S = H_L/R$ (ratio of liquid height to radius of tank) broad and slender tanks are studied with their geometrical dimensions as given in Table 1.

| | Aspect ratio, ($H_L/R$) | Height of water, $H_L$ (m) | Thickness of tank, $t$ (cm) |
|---|---|---|---|
| Broad | 0.6 | 14.6 | 9.73 |
| Slender | 1.85 | 11.3 | 2.44 |

Table 1 Geometrical dimensions of circular tank.

The steel properties are used for modeling the circular tank and the liquid contained in tank is water having density ($\rho_w$) 1000 kg/m$^3$ and bulk modulus ($K$) is 2.05 GPa. The earthquake motions selected for the study are N00E component of 1940 Imperial Valley earthquake recorded at El Centro and N00S component of 1995 Kobe earthquake recorded at Japan Meteorological Agency (JMA). The peak ground acceleration (PGA) of Imperial Valley and Kobe earthquake motions are 0.348 g and 0.84 g, respectively. The two base isolation systems are used for the present study, elastomeric bearing, laminated rubber bearing (LRB) which is commonly characterized by its isolation time period ($T_b$) and damping ($\xi_b$). And sliding system, friction pendulum system (FPS) is characterized by the isolation time period ($T_b$) and friction coefficient ($\mu$). For the present study, isolator properties for the LRB system $T_b = 2$ sec and $\xi_b = 0.1$ and for FPS are $T_b = 2$ sec and $\mu = 0.05$. The LRB is modeled by assigning a cumulative stiffness, $k_b$ and cumulative damping force, $c_b$ by non-linear connector given by Equation (1) and (2), respectively.

$$k_b = M(2\pi/T_b)^2 \tag{1}$$

$$c_b = 2M\xi_b(2\pi/T_b)^2 \tag{2}$$

where $M$ is the total mass of liquid storage tank. The FPS is modeled by assigning coefficient of friction and cumulative stiffness to non-linear connector. The stiffness force for FPS is given by Equation (1). The dynamic analysis is carried for a 20 seconds acceleration time history of earthquake in uni-direction at the rigid base of the tank.

The sloshing displacement is measured at the extreme node from the centre of the tank along the direction of excitation. Figure 3 shows the time history response for broad and slender tank for Imperial Valley, 1940 earthquake ground motion for both LRB and FPS isolation systems compared with the non-isolated tank. Figure 4 shows the time history response for broad and slender tank subjected to Kobe, 1995 earthquake ground motion for isolated and non-isolated tanks. Table 2 gives the peak response values for non-isolated and isolated tank. It can be observed from the responses that due to isolated systems the impulsive component of base shear has reduced more as compared to convective component of base shear. The sloshing displacement is unaffected by both the isolation systems.

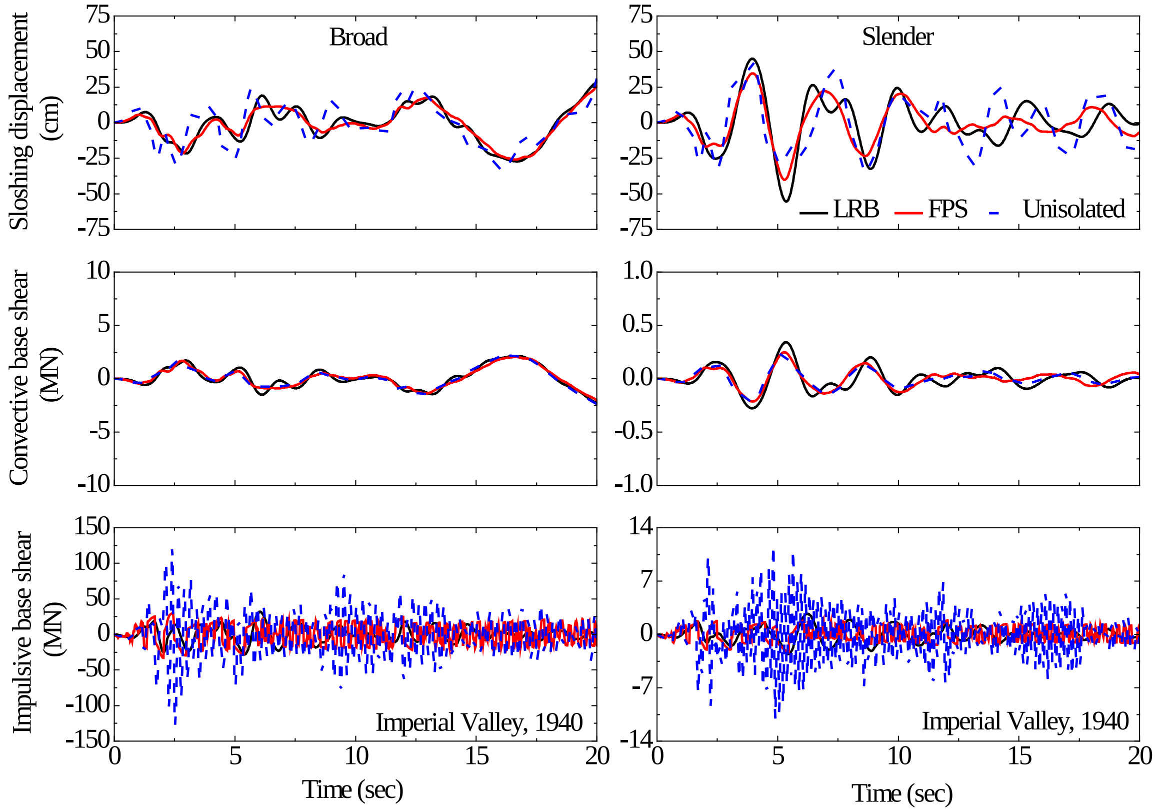


Figure 3 Time history response for 3-D base-isolated circular tanks subjected to Imperial Valley, 1940 earthquake ground motion.

| Tank | Earthquake excitation | Isolation system | Sloshing (cm) | Impulsive base shear (MN) | Convective base shear (MN) |
|---|---|---|---|---|---|
| Broad | Imperial Valley, 1940 | Non-isolated | 61.20 | 127.08 | 5.06 |
| | | LRB | 55.94 | 32.03 | 4.41 |
| | | FPS | 52.84 | 33.02 | 2.92 |
| | Kobe, 1995 | Non-isolated | 44.05 | 258.32 | 3.62 |
| | | LRB | 46.75 | 108.79 | 3.68 |
| | | FPS | 49.33 | 122.55 | 3.89 |
| Slender | Imperial Valley, 1940 | Non-isolated | 41.88 | 12.41 | 0.34 |
| | | LRB | 55.42 | 2.69 | 0.34 |

| | | | | | |
|---|---|---|---|---|---|
| | | FPS | 40.12 | 2.29 | 0.24 |
| | Kobe, 1995 | Non-isolated | 73.96 | 21.34 | 0.42 |
| | | LRB | 98.73 | 8.03 | 0.60 |
| | | FPS | 95.88 | 8.54 | 0.59 |

Table 2 Peak responses for 3-D base-isolated circular tanks.

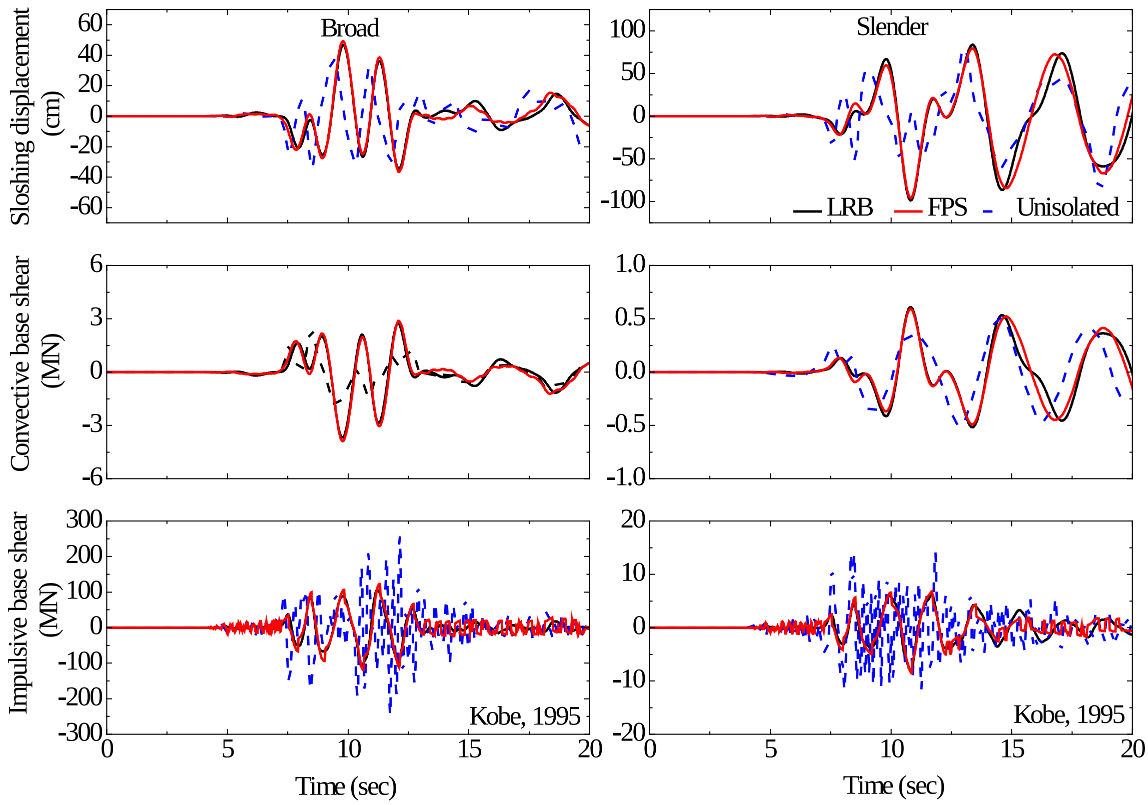


Figure 4 Time history response for 3-D base-isolated circular tanks subjected to Kobe, 1995 earthquake ground motion.

## 4 CONCLUSIONS

In the present study, 3-D FE ground-supported flexible base-isolated cylindrical tank are investigated under uni-directional earthquake ground motions. The coupled acoustic-structure approach of FE method is used for the analyses of tank. The two aspect ratios, broad and slender tanks are studied. The tanks are isolated using elastomeric laminated rubber bearing (LRB) and sliding systems friction pendulum system (FPS). The following conclusions are arrived.

- Both the isolation systems are found effective in reducing the earthquake forces in liquid storage tanks.
- The base shear response is reduced for both broad and slender tanks on application of isolation systems as compared to non-isolated tanks The impulsive component of base shear has major contribution and which has reduced significantly as compared to convective component of base shear.

- The sloshing displacement response has no significant effect on the introduction of isolation.

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