Deformation and Stress Analysis of Cylindrical Acid Storage Tank with Piping Attachments due to Sloshing Upon Kashmir 2005, Earthquake

A. Jehanzeb Joya*[1], Mohamed J. Hyder[2], Yasir Zulfiqar[1]
[1] Department of Mechanical Engineering, Pakistan Institute of Engineering and Applied Sciences, Islamabad, Pakistan
[2] Department of Mechanical Engineering, Capital University of Science and Technology, Islamabad, Pakistan
*thejehanzeb@yahoo.com

Abstract

The efficiency of huge liquid-containing infrastructures to withstand earthquakes without being damaged is a topic that not just engineers are interested in. This is because these facilities are frequently a community's backbone and must be kept operational in the event of an emergency. Furthermore, in some applications, the stored contents, such as acid, may be dangerous, and inadvertent release must be avoided. Seismic response for three HCl fill levels at 25%, 50%, and 75% of tank height on two different shell thicknesses 5mm and 10 mm of circular polyethylene tank having fixed base and piping attachments are investigated. Fluid structure interaction approach is developed in ANSYS Workbench by coupling structural and computational fluid dynamic modules. The focus of this study is to check the deformations and stresses in cylindrical tank and piping attachments in case of real earthquake on a full scale model. It is observed that decrease in shell thickness drastically increases total deformation vulnerable point is the piping attachment with tank while increase in shell thickness reduces equivalent stress making it capable to stand the seismic load. Also, it is observed that the equivalent stress is lower when the fluid is near 0.5h, and greater in other cases 0.25h and 0.75h.

Keywords

Cylindrical tank, sloshing, computational fluid dynamics, acceleration time history, earthquake.

Introduction

The huge volume ground stayed cylinder-shaped tanks are used to stock a variety of liquids, e.g., chemicals, petroleum, drinking water, firefighting and liquefied natural gas. The adequate performance of tanks during strong ground shaking is crucial for modern facilities. Tanks that were ineffectively designed have suffered broad damage during previous earthquakes. Earthquake loss to cylindrical storage tanks can take numerous forms. Beam like bending of the tank wall causes large axial compressive stresses resulting “elephant-foot” buckling of the wall [1].

Sloshing liquid can damage the roof and the top of the tank wall, Sloshing refers to the movement of the free surface of a liquid due to the movement of its container. Liquid sloshing is an important factor to be considered in various areas such as aircraft fuel tank designs, tankers transporting water and other liquids, sloshing of cargo in ships, etc. The large liquid movement during sloshing can result in high impact stresses in the walls. And in extreme cases can cause sufficient moment to negatively affect the stability of the supporting structure. This study investigates the additional stresses developed in structures due to sloshing. The tank wall can be ruptured by high loads in the region of inadequately specified foundation anchors. Base shear can eliminate the friction that causes the tank to slide. Base uplifting in partly anchored and unanchored tanks can cause damage to pipe connections which are unable to accommodate vertical displacements, break the junction of the plate owing to high joint stress and create uneven foundation settling [2]. Initial analytical investigations were bestowed with the hydrodynamics of fluids conducted in rigid tanks with rigid base, one liquid component travels in sloshing movement over a long period of time known as convective liquid while the other component moves firmly against the tank wall. The second half of the liquid, also recognised as the impulsive liquid, has the similar acceleration as the ground and mostly adds to the overturning moment and base shear. The sloshing liquid influences the surface wave height and therefore the demand for freeboard [3].

The impulsive liquid may suffer accelerations many times larger than the peak ground acceleration due to the tank wall's flexibility. As a result, assuming the tank is rigid, the base shear and overturning moment computed might be non-conservative. Tanks supported on flexible foundations suffer base translation and rocking, resulting in longer impulsive durations and typically better effective damping. These alterations might have a substantial impact on impulsive behaviour. Due to its long period of oscillation, both tank wall and foundation flexibility have little effect of the convective (or sloshing) response [4].

A rigidly supported cylindrical HCl acid storage tank is considered for analysis, with fixed input and output pipe attachments. Fluid structure interaction approach is developed in ANSYS Workbench to evaluate the tank using CFX and Structural modules. The detailed sloshing impact due to seismic activity is examined for two different thicknesses of circular polyethylene tank with a fixed base and pipe attachments at three HCl levels of 25%, 50%, and 75%. The major goal of this research is to figure out how cylindrical tanks and pipe attachments will deform and stress in the case of an earthquake.

Problem Formulation

To study the effects of sloshing due to seismic loading, an asymmetric diameter cylindrical tank is modelled. The HCl in the tank is considered initially as a static body and the stresses developed on the supporting structure piping and the tank walls are determined. The sloshing of HCl is then modelled as a transient seismic analysis and the increase in stresses developed due to sloshing is determined. This fluid-structure interaction effect on deflection of the structure, at different cylinder thicknesses and HCl levels by the application of the earthquake peak ground acceleration (PGA) are studied [5].

Structural Modelling

The cylinder is modelled as, asymmetric diameter cylindrical tank of dimensions having wall thickness of 10 mm and 5mm, diameter 2 m and height 3 m, with fixed inlet and outlet scheduled 40 piping attachment having nominal pipe diameter of 76.2 mm. At the height 152.4 mm from the base, the outlet piping system is linked to the tank discharge point via an Integrally Molded Flanged Outlet (IMFO) system. Similarly, inlet piping system is connected to the tank intake point at the depth of 152.4 mm from the top. The tank is supported by fixed support at the base. (see **Figure 1**)

Material Selection

The tank is made of polyethylene, which is popular in the chemical industry because of its chemical resistant qualities and ease of manufacturing. Polyethylene has the following material properties: (see **Table 1**) [6], [7].

Table 1 – Material Properties

Density	Yield Strength	Ultimate Strength	Poisson's Ratio	Melting Point
950 kg/m³	25 MPa	33 MPa	0.46	115-135 ^{O}C

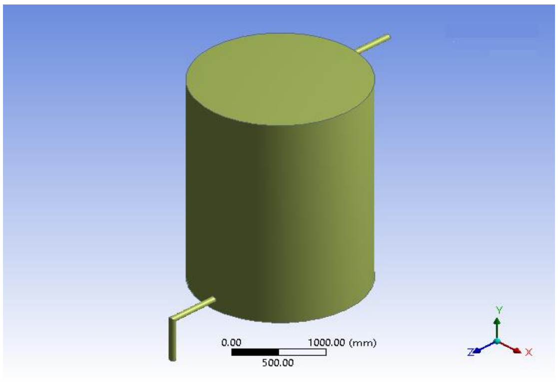

Figure 1. Tank-Piping System Model

Seismic Input

In ANSYS Version 11 and later, the acceleration time histories might be used in the command that establishes degree-of-freedom (DOF) constraints at nodes for transient seismic analysis. In other words, as a base excitation, any number of degrees of freedom may now be applied to specified nodes [8].

Acceleration due to gravity is assigned in the vertical direction and earthquake load is assigned along the longer dimension of the tank. Acceleration data of Kashmir earthquake of magnitude 7.6 (Mw) on 8:50 a.m. local time (3:50 UTC), (see **Figure 2**). The epicenter at a depth of 26 km (USGS 2005) was reported to be located at 34.49° N and 73.63° E, approximately 10 kilometers northeast of Muzaffarabad and 90 kilometers north of Islamabad. [9], is assigned as lateral earthquake load to the supports.

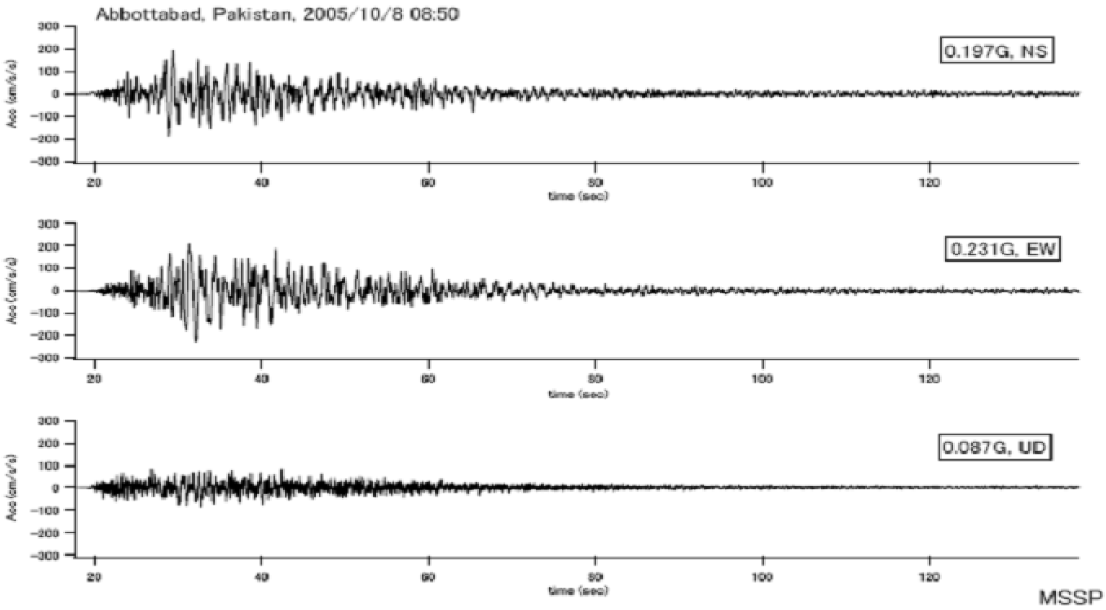

Figure 2. The accelerogram obtained at Abbottabad: (a) PGA=0.231g, east-west component, (b) PGA=0.197 g, north-south component and (c) PGA=0.085g, vertical component. (courtesy of Pakistan Atomic Energy Commission, Micro Seismic Studies Program, 2005.)

Analysis and Solution

Transient seismic analysis is performed in Fluid Flow CFX solver using volume of fluid with K-epsilon turbulence model under boundary conditions free slip wall [10]. Assuming fluid incompressible and inviscid. The earthquake acceleration is applied along the z direction. The HCl fill levels are varied from 0.25h, 0.5h and 0.75h, of tank depth. The total pressure generated due to sloshing in tank at different depths of HCl are analyzed and imported in a Structural solver for each case to study the structural effects. Obtaining the seismic response of tank by FSI approach.

Model Validation

FSI model is compared and validated with different design codes and standards like after reaching at the converged and steady solution, the CFX and Structural results are compared with available Storage Tank Design Codes i.e. Eurocode-8 part 4 & IITK-GSDMA, D1998-15 ASTM-2015 and ASME B16.5-2003. The validation procedure followed in this is also adopted in author's recent publications[10], [11].

1. The imbalances in the CFD solution are less than 1%.
2. The difference between the hydrostatic pressure in the tank and the analytical data is less than 0.08%.
3. Average percentage difference in total pressure time history is less than 0.4%.
4. The structural solution imbalances are less than 0.5% for load and 5% for DOF.

Model -I

The analyses are carried out at the same loading and boundary conditions for the fluid (HCl) filled height of up to 25% of the tank (0.25h) at two distinct shell walls thicknesses of 10 and 5 mm (see **Figures 3 to 8**).

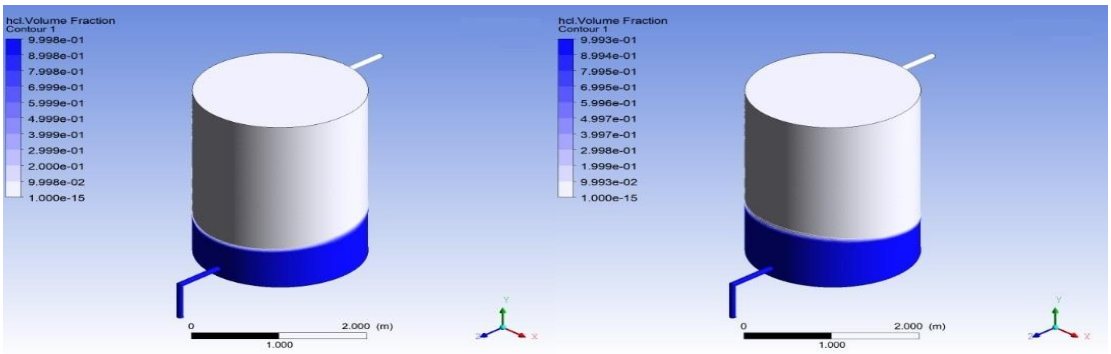

Figure 3. Sloshing of HCl in 25% filled tank

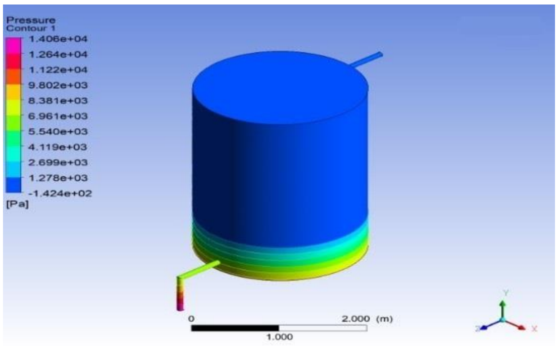

Figure 4 (a). Pressure when HCl as static body

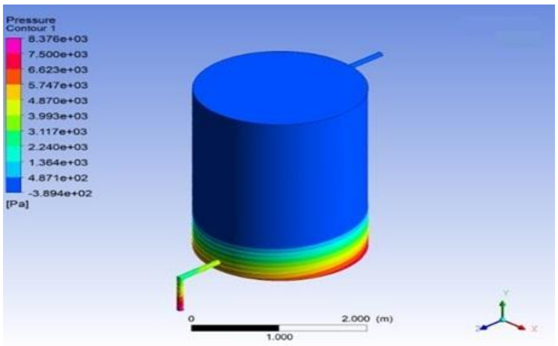

Figure 4 (b). Pressure due to sloshing in 25% filled tank

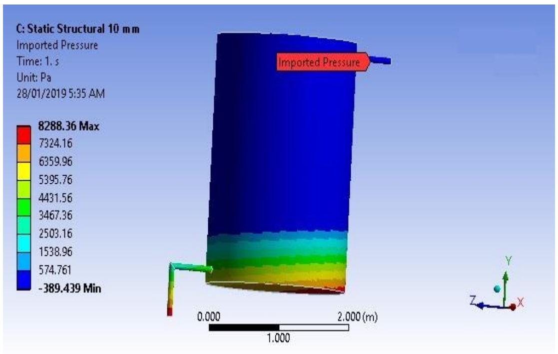

Figure 5. Pressure imported due to sloshing of HCl

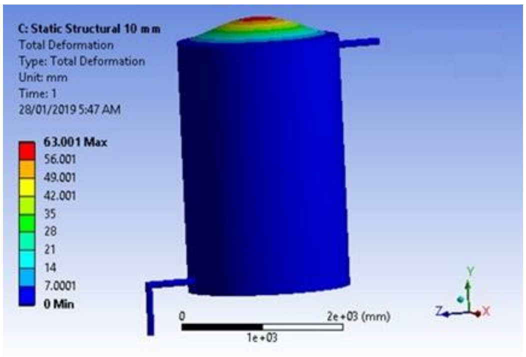

Figure 6 (a). Total deformation in thickness 10 mm

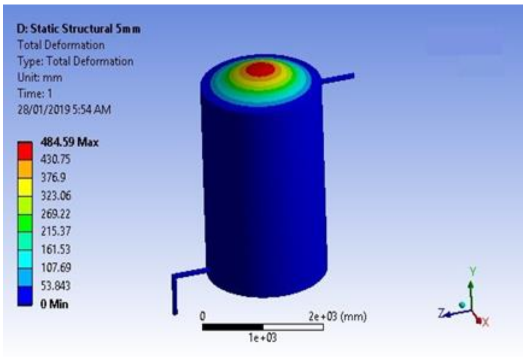

Figure 6 (b). Total deformation in thickness 5 mm

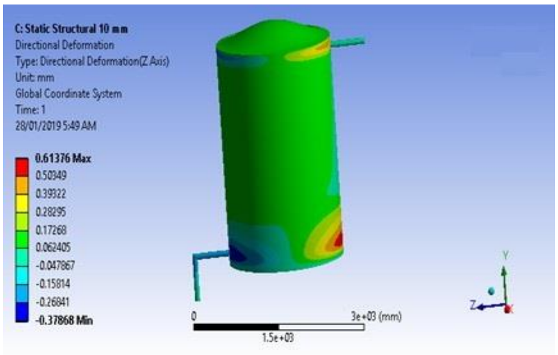

Figure 7 (a). Directional Deformation in thickness 10 mm

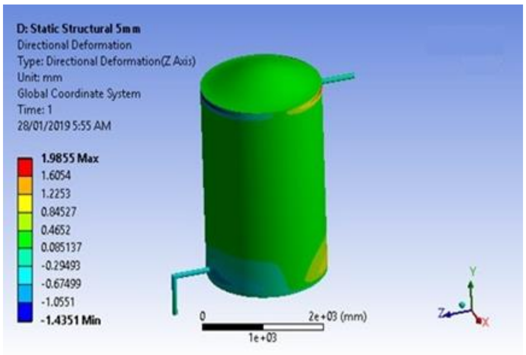

Figure 7 (b). Directional Deformation in thickness 5 mm

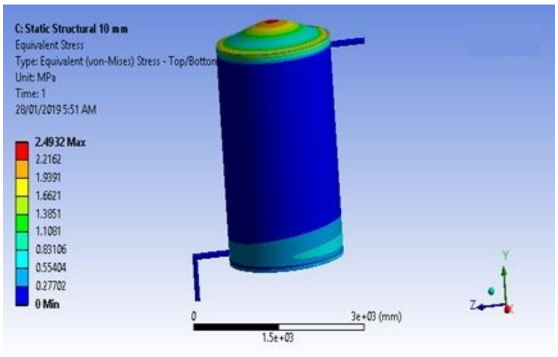

Figure 8 (a). Equivalent Stress wall thickness 10 mm

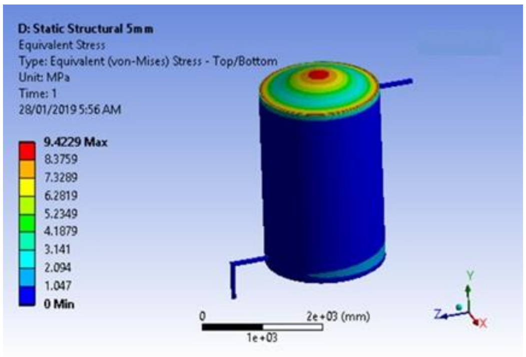

Figure 8 (b). Equivalent Stress wall thickness 5 mm

Model -II

The analyses are carried out at the same loading and boundary conditions for the fluid (HCl) filled height of up to 50% of the tank (0.5h) at two distinct shell walls thickness of 10 and 5 mm (see **Figures 9 to 14**).

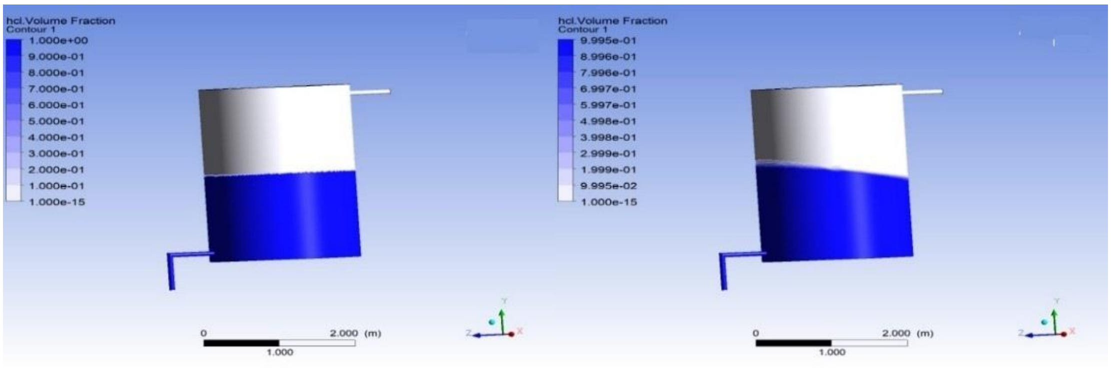

Figure 9. Sloshing of HCl in 50% filled tank

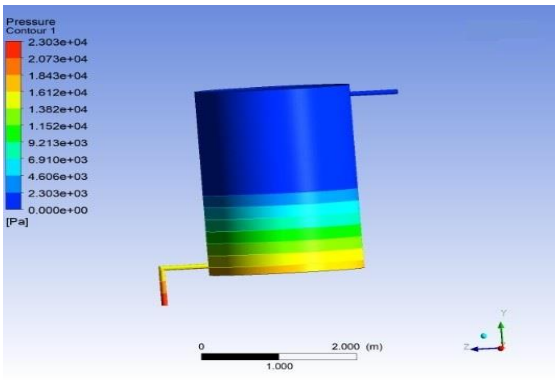

Figure 10 (a). Pressure when HCl as static body

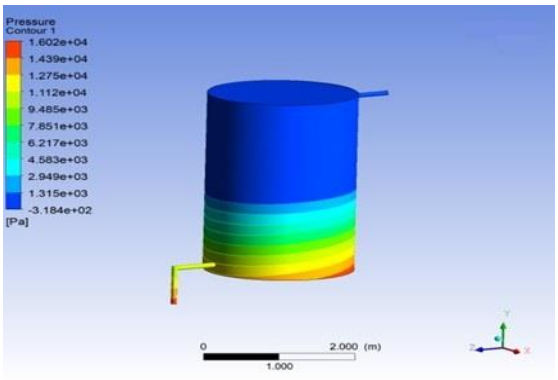

Figure 10 (b). Pressure due to sloshing in 50 % filled tank

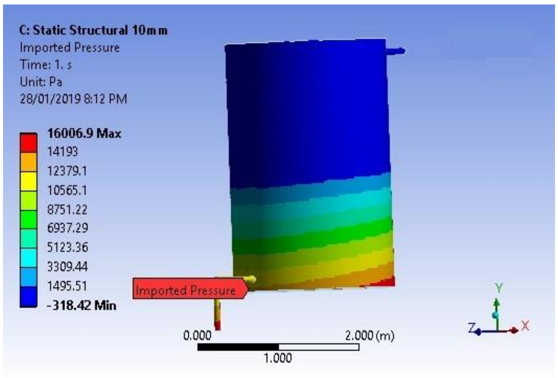

Figure 11. Pressure imported due to sloshing of HCl

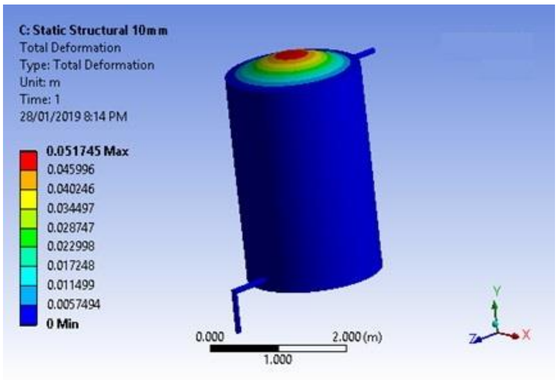

Figure 12 (a). Total deformation in thickness 10 mm

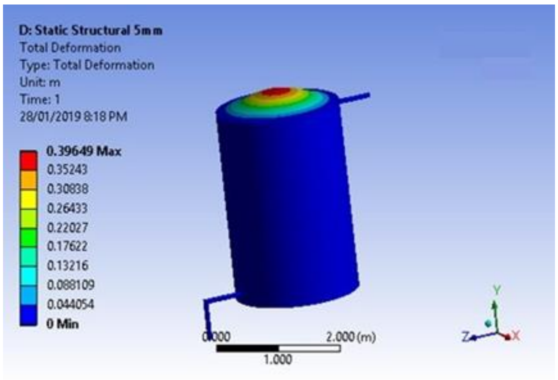

Figure 12 (b). Total deformation in thickness 5 mm

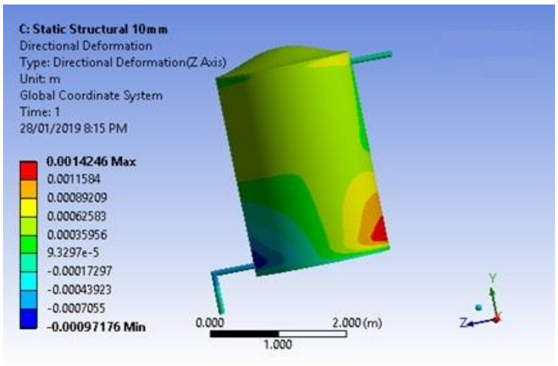

Figure 13 (a). Directional Deformation in thickness 10 mm

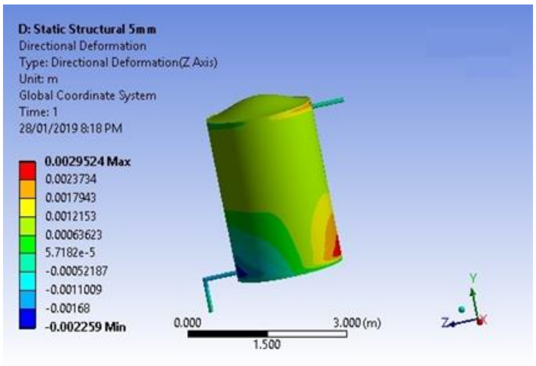

Figure 13 (b). Directional Deformation in thickness 5 mm

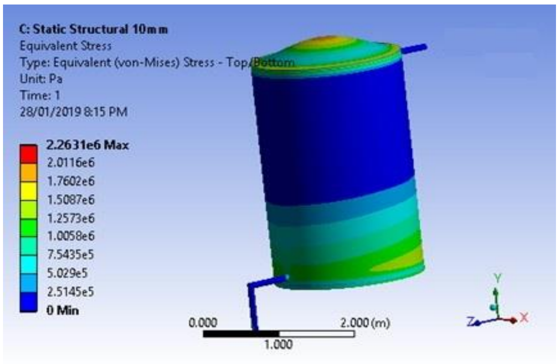

Figure 14 (a). Equivalent Stress wall thickness 10 mm

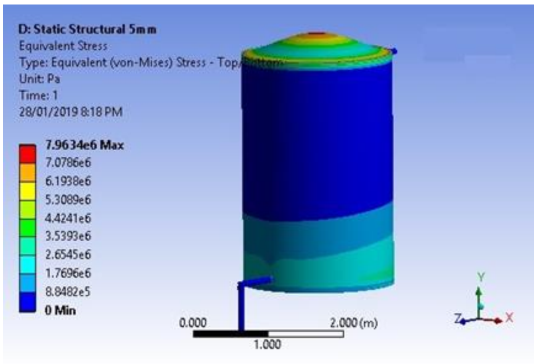

Figure 14 (b). Equivalent Stress wall thickness 5 mm

Model -III

The analyses are carried out at the same loading and boundary conditions for the fluid (HCl) filled height of up to 75% of the tank (0.75h) at two distinct shell walls thickness of 10 and 5 mm. (see **Figures 15 to 20**)

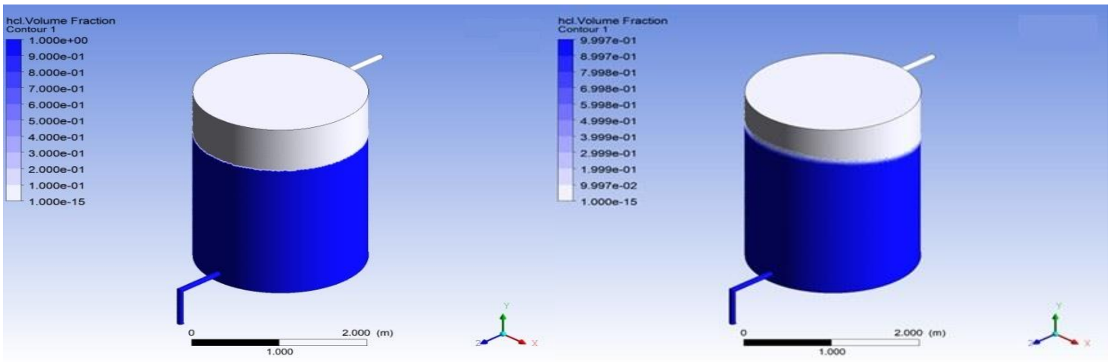

Figure 15. Sloshing of HCl in 75 % filled tank

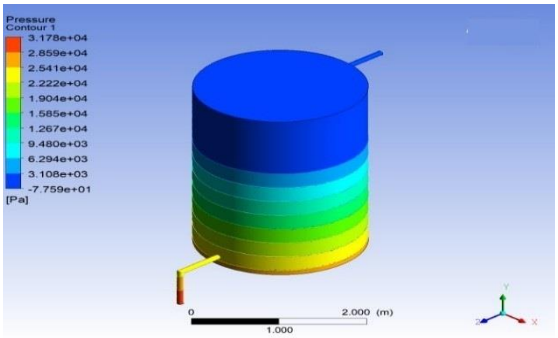

Figure 16 (a). Pressure when HCl as static body

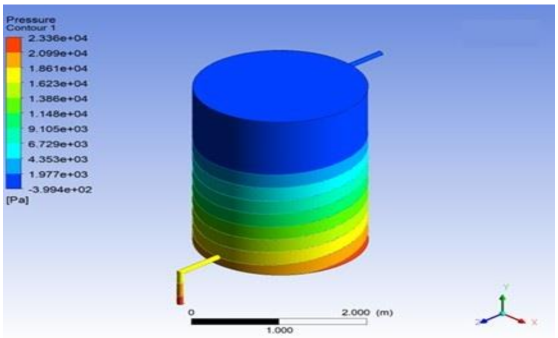

Figure 16 (b). Pressure due to sloshing in 75% filled tank

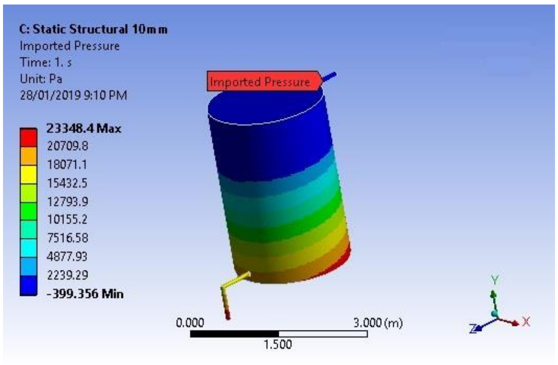

Figure 17. Pressure imported due to Sloshing of HCl

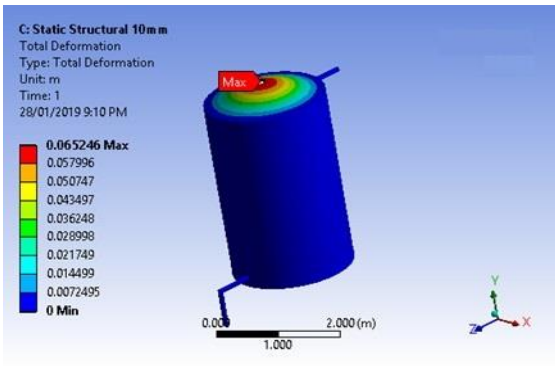

Figure 18 (a). Total deformation in thickness 10 mm

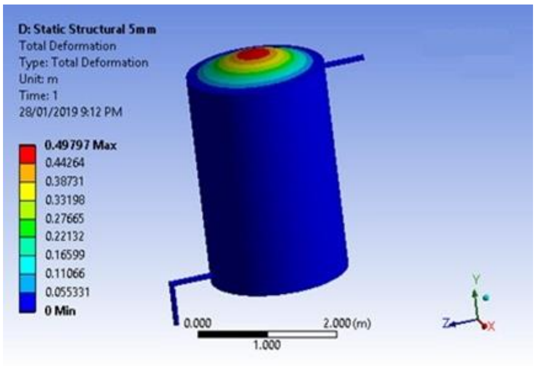

Figure **18 (b).** Total deformation in thickness 5 mm

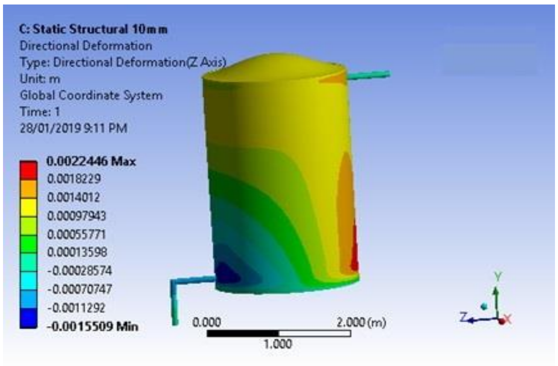

Figure 19 (a). Directional Deformation in thickness 10 mm

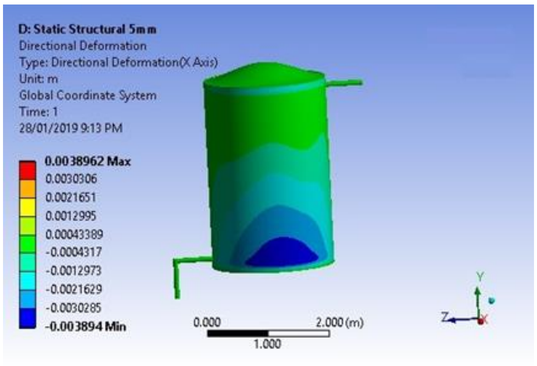

Figure 19 (b). Directional Deformation in thickness 5 mm

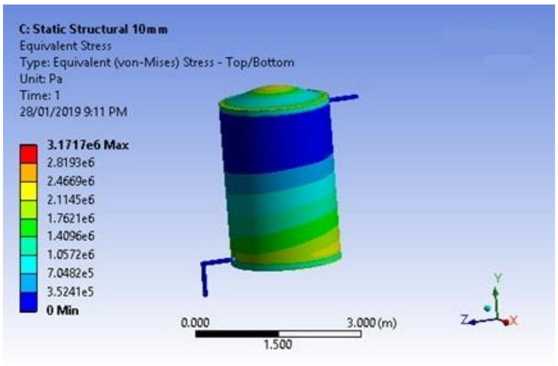

Figure **20 (a).** Equivalent Stress wall thickness 10 mm

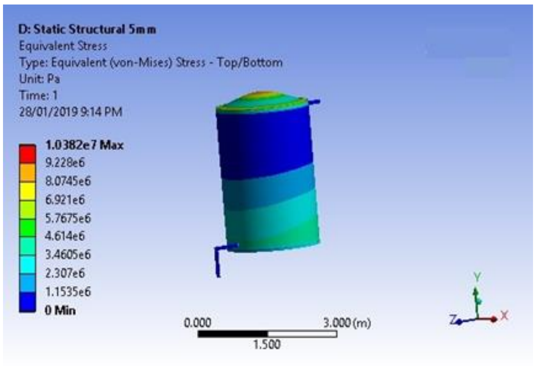

Figure 20 (b). Equivalent Stress wall thickness 5 mm

Results and Discussion

Comparison between static and sloshing behavior of the fluid.

Pressure Comparison

The pressure on the structure wall due to the sloshing of HCl in the tank is compared to the pressure developed (see **Table 2**) when HCl is modelled as a static body (see **Figures 4, 10 &16**) the sloshing of fluid helps dissipate energy transferred to the structure during an earthquake.

Table 2 – Pressure Comparison

Model	Fluid depth (m)	Max. Pressure as HCl static (Pa)	Max. Pressure due to Slosh (Pa)
I	0.25h	14064	8288.36
II	0.5h	23032.3	16006.9
III	0.75h	31780	23348.4

Deformation Comparison

The earthquake acceleration is applied along the z direction (along with piping attachment of the tank) with gravitational accelerations, total deformations (see **Figures 6,12 &18**) and directional deformation (see **Figures 7,13 &19**) are recorded and results are compared at three fluid levels and two different thickness of tank shell (see **Tables 3 & 4**).

Table 3 – Total Deformation

Model	Fluid depth (m)	Thickness 10 (mm)	Thickness 5 (mm)
I	0.25h	63.001	484.59
II	0.5h	51.745	396.49
III	0.75h	65.246	497.97

Table 4 – Directional Deformation

Model	Fluid depth (m)	Thickness 10 (mm)	Thickness 5 (mm)
I	0.25h	0.61376	1.9855
II	0.5h	1.4246	2.1524
III	0.75h	2.2446	3.8962

Equivalent Stress Comparison

Cylindrical HCl storage tank analyzed are assumed to be fixed at their base with fixed inlet and outlet piping attachment. Three HCl levels of 25 %, 50% and 75% at two different thickness of circular polyethylene tank having fixed base and piping attachments are analyzed (see **Figures 8,14 & 20**) and following maximum equivalent stress developed due to sloshing upon seismic loading are recorded (see **Table 5**).

Table 5 – Max Equivalent Stress (MPa)

Model	Fluid depth (m)	Thickness 10 (mm)	Thickness 5 (mm)
I	0.25h	2.493	9.4229
II	0.5h	2.2631	7.9634
III	0.75h	3.17	10.382

Conclusion

The conclusions drawn based on the study are:

- The overall distortion increased by more than 7.5 times when the cylinder shell thickness is reduced from 10 mm to 5 mm, increasing base uplift, causing bulging and rupturing pipe attachment with the tank.
- Reducing the cylinder shell thickness by half from 10 to 5 mm, increase base shear and stresses on piping critical components such as elbows and flanges.
- The maximum equivalent stresses are reduced when the cylinder shell thickness is increased, allowing it to withstand the seismic load.
- It is observed when the tank is approximately half-full, the maximum equivalent stress is lower, and the maximum equivalent stress is higher when the tank is filled at either 25% or 75% of its height.

Nomenclature

HCl	hydrochloric acid
h	height of fluid [m]
PGA	Peak Ground Acceleration [m s^{-2}]
IMFO	Integrally Molded Flanged Outlet
FSI	Fluid Structure Interaction
DOF	Degree of Freedom

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