# MITIGATION OF SLOSHING EFFECTS IN HIGH LEVEL LIQUID WASTE (HLW) STORAGE TANK FOR NUCLEAR SPENT FUEL APPLICATIONS

V.S. SANAPALA, M. ASHWIN, T. SELVARAJ, K. RAJAN and K. ANANTHASIVAN\*

1Reprocessing Group, Indira Gandhi Center for Atomic Research, Department of Atomic Energy, India

Email contact of corresponding author: asivan@igcar.gov.in

**Abstract**

High level liquid waste is often stored in large capacity horizontal cylindrical tanks especially in fast reactor fuel reprocessing plants. However, these huge tanks in partially filled condition pose safety concerns due to seismicity. Violent sloshing during an earthquake-induced Fluid-Structure Interaction (FSI) can lead to catastrophic effects such as structural failures, gas entrainment and roof impact buckling etc. Therefore, it is important to ensure safe design margins and develop methodologies to overcome a wide range of possible scenarios at the design stage itself. In this regard, a Computational Fluid Dynamics (CFD) based numerical study is carried out to understand the liquid sloshing dynamics in horizontal cylindrical tank subjected to harmonic excitations. For the purpose of tracking the free surface during the simulation, Volume of Fluid method (VOF) is to be employed. An optimum baffle configuration is recommended to suppress the free surface fluctuations and the associated slosh forces. Temporal snapshots of free surface interface and hydrodynamic pressures time histories are presented at different locations inside the tank under these conditions. Furthermore, the effectiveness of the baffle geometry is tested for a seismic excitation in mitigating the free surface fluctuations and thereby forces on tank walls.

## INTRODUCTION

Sloshing is a phenomenon of oscillation of the unrestrained free surface of the liquid in a partially filled container. It has strong influence on dynamic stability of aircraft, missiles, Storage tanks and nuclear reactors etc., which can lead to tank roof impact, wave breaking and mixing of air and liquid when the sloshing frequencies are close to the system natural frequencies [1]. Therefore, it is of great concern to designers of various fields of engineering. In case of nuclear applications, the radioactive liquid waste is often stored in large capacity horizontal cylindrical tanks [2]. Any such failure may cause catastrophic effects such as release of radioactivity. Therefore, designing safe structures against such eventualities is vital to our survival.

Linear potential flow theory is widely employed by many authors in evaluating sloshing induced loads for various applications. Karmanos [3] has developed a mechanical spring-mass-damper model to account for the sloshing effects in half-full horizontal cylindrical vessels, under external excitation along the direction of the longitudinal vessel axis. Sigrist, et al. [4] have carried out the dynamic analysis of nuclear reactor to compute the eigen modes and the dynamic response of the fluid–structure coupled system characterized by added mass, added stiffness and coupling effects. However, these analytical methods do not offers physical insights into sloshing mechanisms. Later, Chen et al. [5] have proposed a numerical method to analyze the response for seismic excitation of cylindrical tanks. They have taken the nonlinear hydrodynamic effects into account to study the response of wave height on the liquid surface, and shear force and overturning moment at the base wall and its dynamic stability [6]. Lakis and Neagu [7] have developed a semi-analytical approach to study free surface effects on the dynamics of cylindrical shells partially filled with liquid. A hybrid finite element method was developed through a combination of the classic finite element method and Sanders’ equations for cylindrical shells.

The reduced effect of sloshing response with the provision of baffles has seen a progressive growth during the last decade. The dynamic interaction that exists between the liquid and elastic tank–baffle (to reduce the sloshing response of fluid) system has been considered to evaluate the coupled response of liquid and tank–baffle system. The dynamics of liquid sloshing and its control in a storage tank is studied under horizontal [8,9] as well as vertical excitations [10]. The effect of providing baffles on the slosh frequencies and coupled vibration frequencies in the liquid filled composite tanks have been studied by Biswal and Bhattacharya [11].

Even though problem of liquid sloshing is well studied, a limited literature is available on the mitigation of damage of horizontal cylindrical tanks due to liquid sloshing in storage tanks. In the present study, a 2D horizontal tank with a tori-spherical head is considered under harmonic wave excitation in the non-linear range of amplitude subjected to resonant excitation conditions. In this study, we have adopted a finite volume approach by solving incompressible Navier–Stokes equations. Effect of introducing a vertical baffle is studied through implementing a fully nonlinear solid wall boundary in order to understand the suppression effect of free surface fluctuations under the harmonic as well as seismic input loading conditions.

## Numerical methodology and validation

The mass and momentum conservation equations governing the fluid behavior in a tank are as follows:

Mass conservation : $\frac{∂u}{∂x}+ \frac{∂v}{∂y}=0$ (1)

Momentum conservation : $\frac{∂u}{∂t}+u\frac{∂u}{∂x}+v\frac{∂u}{∂y}=-\frac{1}{ρ}\frac{∂P}{∂x}+ϑ\left(\frac{∂^{2}u}{∂x^{2}}+\frac{∂^{2}u}{∂y^{2}}\right)+f$ (2)

$$\frac{∂v}{∂t}+u\frac{∂v}{∂x}+v\frac{∂v}{∂y}=-\frac{1}{ρ}\frac{∂P}{∂y}+ϑ\left(\frac{∂^{2}v}{∂x^{2}}+\frac{∂^{2}v}{∂y^{2}}\right)+g$$

Where (*u, v*) is the fluid velocity in (*x, y*) directions, *P* is the pressure, $ϑ$ is the kinematic viscosity, g is the acceleration due to gravity, t is the time and *f* is the external force. Under the dynamic influence of excitation force, the surface tension force can be assumed to be neglected.

The computational procedure involves tracking this free surface interface which is handled by the well known volume of fluids (VOF) technique. The Volume of Fluid (VOF) tracks the interface between the two fluids (air and water) during simulations. The governing transport equation for the phase fraction

 $\frac{∂α}{∂t}+ u\frac{∂α}{∂x}+v\frac{∂α}{∂y}=0$ (3)

where, $α$ represents the volumetric fraction between air and water, which is taken as 0 for air, 1 for water and in between 0 and 1 at the interfaces.

The velocity boundary condition on the walls that are not at all exposed to the free surface (tank bottom), satisfy the no-slip boundary condition ($u=v=0$). The velocity boundary condition specified on the walls that are in contact with the free surface is not well posed due to the contradiction of the moving free surface and a no-slip condition on the bounding wall. The resulting boundary conditions for the vertical walls are$ u=0$; $\frac{∂v}{∂x}=0$. The dynamic boundary condition on the bottom wall yields$ μ\left(\frac{∂u}{∂y}+\frac{∂v}{∂x}\right)=0 on y=0$. The harmonic displacement is enforced such that, f =-ω2$x\_{e}=-ω^{2}X sin(ωt)$, where, X is the amplitude of the excitation and $ω $is the excitation frequency.

The governing fluid flow equations are solved numerically using OpenFOAM, an open source Computational Fluid Dynamics (CFD) solver, which employs a Finite Volume based algorithm. The grid size sensitivity and time step size sensitivity simulations have been carried out similar to the earlier work on liquid sloshing under horizontal and vertical excitations (see Sanapala et al.[9-10] for more details).

The computational domain considered is a two-dimensional horizontal cylindrical tank of length of L (= 12.75 m) and diameter, D (= 4.3 m), which is partially filled with water to a depth of h (= 1.5 m). The cylindrical shell is closed with torispherical heads with knuckle and crown radius of 0.1D and D respectively. Figure 1 shows the schematic of the computational domain and the coordinate system. A cartesian coordinate system is used with the OXY plane on the mean free surface, with O as the origin for the X and Y axes. The pressure probes (P1 to P7) are located on the tank at different location as shown Fig.1.

## Results and discussion

To start with, numerical simulation of a liquid sloshing in a horizontal tank subjected to harmonic excitation is investigated in section 3.1. In section 3.2.1, the sloshing dynamics under the influence of a passive baffle is presented. An optimal configuration from the harmonic excitation is chosen to investigate its efficacy under an earthquake excitation in section 3.2.2.

### Sloshing in horizontal cylindrical tanks

The forced excitation of the tank is imparted through a horizontal displacement initiated at the base of the tank. The present simulations monitor and validate the free surface profile as well as the pressure distribution on the bottom wall. Firstly, the partially filled (h= 1.5m) tank is excited with a forcing amplitude of x = 0.01m at or near the resonant excitation frequency, ω = 0.933Hz to emphasize the wave features inside the tank. Figure.2 depicts the numerical snapshots of volume fraction at different time levels. Starting from an equilibrium state at time t=0, when the tank is excited, the free surface exhibit a standing wave feature initially as shown in Fig. 2(c) for t = 120.6s. At t= 130.55s, it shows the run up on to the right tank head. As there are no wall effects due to the tori-spherical head, these standing wave features are continued for longer times. The advancing wave front is clearly visible even at t= 190.10s.

The temporal variation of dynamic pressure at three different locations viz., at P1(0.956,0), P2(0.12, 1.37), P3(0.087,1.57) ) and P4(0.067,1.75) (as specified in Fig.1) was closely monitored as a function of time. These locations are chosen mainly to understand the effect of torispherical head rather than a flat closure. It is interesting to note that the measured pressure near the free surface indicate only positive impact pressure peaks with flat line in between those peaks. This may attributed to the curvature of the head that cause relatively stand still nature of the fluid in the torispherical head region. However, the numerically estimated pressure histories are bounded by a maximum value nearly after t = 180s. Correspondingly, a peak dynamic pressure of 4.2kPa is found at P1.

### Control of Sloshing in horizontal cylindrical tanks: with baffle

The sloshing dynamics in a liquid storage tank subjected to external excitation can be suitably controlled by placing baffles along its motion path. This would not only result in additional damping effect, but also acts as a sacrificial structure. However, the design configuration and position of these baffles require detailed simulations and optimization. In this section, the efficacy of a vertical baffle under resonant harmonic as well as seismic excitations is investigated.

#### Harmonic excitation

Numerical simulations are performed for all the above case with and without baffle. Magnitude of volume fraction color maps compared with and without an internal baffle indicated a significant reduction in the sloshing fluctuations. The variation of the associated pressure field fluctuations presented in Fig.4 is reflective of the free surface fluctuations. It is clear that when the baffle is introduced inside the tank, the liquid sloshing is suppressed due to the augmentation of the blockage effect of the baffle, which results in additional viscous energy dissipation. However, any large scale forces on this structure and the resulting fatigue can easily make it into a sacrificial structure under resonant excitation. From Fig. 4, the hydrodynamic pressure time history measured at P1 has indicated that the peak pressure with an intermediate baffle plate is marginally reduced the response from 4.2kPa to 0.25kPa. Figure .5 presents the distribution of total pressure field on the torispherical tank head along its curvature at different time levels.

#### Seismic excitation

Horizontal cylindrical tanks subjected to earthquake excitation is a serious engineering problem with disastrous consequences, more, so for the nuclear spent fuel liquid waste. To this end, a typical seismic excitation produced during El Centro ground motion for a period of 53.74s with a maximum peak ground acceleration (PGA) of 0.33g is used as input. The acceleration of the input seismic excitation, which encompasses a wide range of frequencies. For two typical extremities, identified at 33.65s and 40.3s, the magnitude of volume fraction color maps are presented in Fig. 6. To enable a uniform comparison, the magnitude range for the color map is kept constant. A reduction in the amplitude of the fluctuations due to the presence of an optimal baffle can be particularly noticed in the case of seismic input spectra as well. The cessation of stronger force fluctuations can be seen, in the presence of an optimal baffle. Similarly, the hydrodynamic pressure time history measured at P1 in a tank with and without baffle is presented in Fig. 7. The maximum free surface displacement without the baffle and with an optimal baffle are reduced by more than 5-10 times. In summary, it can be noticed that the baffle configuration which was optimized by analyzing the harmonic excitations, can still be rendered as a useful tool in the analysis of seismic excitations.

## SUMMARY

Numerical simulations have been performed to understand liquid sloshing dynamics in a waste storage tanks considering a two-phase liquid flow inside a tank subjected to external harmonic excitations. The following are few observations in the present investigation:

* Magnitudes of peak pressure show an irregular tendency even though excitation is regular as the sloshing flows are highly nonlinear and stochastic in nature.
* Effect of tank head geometry on sloshing response with and without baffle is investigated. A higher positive peak when the wave front is travelling upwards, whereas, smaller negative peaks were noticed in the measured hydrodynamic pressure while falling downwards.
* Systematically investigated the effect of vertical baffle configuration under harmonic and seismic excitations.
* The optimum baffle configuration is found to be effective in controlling the sloshing amplitudes under harmonic and seismic excitation as well.



Fig. 1. Geometric details and flow domain of interest with pressure probes (located at

P1, to P7) for a horizontal cylindrical tank.

|  |  |
| --- | --- |
| animate.0000.jpg(a) t=0s | 12550.png(b) t=105.5s |
| 12060.png(c) t=120.6s | 13060.png(d) t=130.55s |
| 18015.png(e) t=180.15s | 19010.png(f) t=190.10s |

Fig. 2. Color maps of phase fraction (α) captured at different time levels t (a) 0s, (b) 105.5s, (c) 120.6s, (d) 130.55s, (e) 180.15s and (f) 190.10s.



Fig. **3**. Temporal variation of dynamic pressure measured on the tank head at different locations (a) Near the tank bottom wall (P1) (b-c) just below the free surface (P2& P3) and (d) near the free surface (P4).



Fig. **4**. Distribution of total pressure fields on torispherical head of a cylindrical tank at different time levels



Fig. **5**. Temporal variation of hydrodynamic pressure measured at P1 in a tank with and without an internal baffle.

|  |  |
| --- | --- |
| 3365.png  | 1200.png |
| (a) t=33.65s |
| 4030.png | 1810.png |
| (b) t=40.30s |

Fig. **6**. Color maps for the liquid phase fraction without baffle (left column) and with baffle (right column) in tank subjected to ElCentro earthquake at same time levels.



Fig. **7**. Temporal variation of hydrodynamic pressure measured at P1 in a tank subjected to ElCentro earthquake with and without an internal baffle.

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