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Effect of baffle size and orientation on lateral sloshing of partially filled containers: a numerical study

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ABSTRACT
The fluid sloshing in partially filled road tankers has significantly increased the number of road accidents for the last few decades. Significant research is needed to investigate and to come up with optimum baffles designs that can help to increase the rollover stability of the partially filled tankers. In this investigation, a detailed analysis of the anti-slosh effectiveness of different baffle configurations is presented. This investigation extends the already available studies in the literature by introducing new modified rectangular tank's shapes that correspond to maximum rollover stability as compared to the already available standard tank designs. The various baffles configurations that are analysed in this study are horizontal, vertical, vertical–horizontal and diagonal. In the current study, numerical investigations are performed for rectangular, elliptical and circular tank shapes. Lateral sloshing, caused by constant radius turn manoeuvre, was simulated numerically using the volume-of-fluid method, and effect of the different baffle configurations was analysed. The effect of tank fill levels on sloshing measured in terms of horizontal force and pressure moments is also reported for with and without baffles configurations. Vertical baffles were the most effective at reducing sloshing in modified rectangular tanks, whereas a combination of horizontal and vertical baffles gave better results for the circular and elliptical tanks geometries.

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KEYWORDS
Fluid sloshing; rollover stability; baffles configurations; tanker's shapes

1. Introduction

Hazardous goods are normally transported in heavy-duty trucks, which comprise approximately 10% of the total road transport (Staebler, 2001). Any accident during transportation of such goods can incur monetary loss as well as put safety of human life and environment in grave jeopardy. The danger is even more if the liquid payloads are flammable. The level of damage involved in such a catastrophic

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incident was, unfortunately experienced during accidents in the past such as, San Carlos, Spain (Klaus, 2002) and Herborn, Germany (Gosta, 1981). Study of accidents statistics reveals that the main reason behind these kinds of accidents is the rollover of the vehicle. The National Highway Traffic Safety Administration (USA) has documented over 16,000 rollover accidents per annum involving heavy-duty commercial vehicles (Blower & Pettis, 2001, 2002). One of the main causes of these rollovers is fluid sloshing, which is defined as the periodic motion of fluid with the free surface in a liquid container. Any section that is filled with less than its full capacity allows the movement of the liquid inside the tank, producing the slosh phenomena. Sloshing can be classified into two categories; longitudinal slosh and lateral slosh. Longitudinal slosh is generally encountered during application of brakes and can cause failure of brakes. Lateral slosh, on the other hand occurs due to lateral movements (e.g. Lane change or direction change), and since the fluid inside the tank responds to the manoeuvre-induced lateral acceleration by displacing laterally. This lateral movement of the liquid is responsible for the rollover of the vehicle. Probability of rollover is very small in totally filled tankers because of the confinement of the fluid, but in partially filled tankers, this increases due to the dynamic shifting of centre of gravity (CG), and manoeuvre-induced forces and moments. Although, longitudinal sloshing is considered more severe than lateral sloshing due to the length of a truck greater than its width, it is the lateral sloshing that causes rollovers, and is of interest here.

Since sloshing is common in fuel tanks of automobiles, aircrafts, tankers and large ships, understanding of the sloshing phenomenon has interested researchers over a long time. Rayleigh (1876) used a pendulum to simulate the dynamic effects of sloshing and obtained the correct lengths for regular pendulums that matched the fluid natural frequencies. Aliabadi, Andrew, and Jalal (2003) simulated fluid sloshing using pendulum models both experimentally and computationally. The computational methods employed provided excellent stiffness and inertia values for fluid sloshing. Abramson and Silverman (1966) on reviewing the work done in the field of liquid slosh concluded that the first mode of oscillation is critical in partially filled containers. As sloshing in partially filled containers affects both the structural as well as rollover stability of the vehicle, attempts have also been made to reduce sloshing and enhance damping of liquid oscillation. Studies have been conducted to investigate slosh-damping effectiveness of devices such as positive expulsion bags (Stofan & Sumner, 1963), diaphragms (Ballinger, Lay, & Tam, 1995), baffles (Cho, Lee, & Ha, 2005). Since baffles provide large damping for comparatively low weight, this technique of reducing slosh is considered to be the most promising. Baffles configuration, width, thickness, location and flexibility are important parameters that affect the damping and frequency of oscillations. Silveira, Stephens, and Leonard (1961) conducted an experimental investigation to determine the slosh-damping characteristic of different baffles configurations. Results showed that fixed ring baffles were most effective in terms of reducing slosh magnitude and increasing damping factor.

Studies reported above were driven by aerospace applications, mostly involving only the sinusoidal excitation. Hence, these cannot be applied directly to road vehicle applications, which is the focus of current study. Effect of baffles on longitudinal and lateral sloshing in partially filled containers has only been studied scarcely. Most of the studies have relied on experimental or computational methods, due to the complexity in application of boundary conditions to achieve an analytical solution. Yan and Rakheja (2009), modelled longitudinal fluid slosh within a tank containing baffles using the Navier–Stokes equations coupled with the volume-of-fluid (VOF) equation in Fluent. Straight-line braking properties for different fill volumes and magnitudes of braking treadle pressure at constant cargo load were investigated. Degradation of the braking performance of partly filled tanker was observed; particularly in the absence of baffles. Modaressi-Tehrani, Rakheja, and Sitharu (2007) subjected a cylindrical tank to lateral, longitudinal and combinations of longitudinal and lateral acceleration numerically to investigate the significance of resulting destabilising forces and moments caused by the transient fluid slosh. Both pure (without baffles) and with-baffles configurations were modelled. Results showed that transverse baffles help in reducing fluid sloshing only in the longitudinal direction and are not much helpful in reducing sloshing in lateral direction. Similar observations were made by Yan, Rakheja, and Siddiqui (2009), after carrying out an experimental investigation to determine the anti-slosh effectiveness of baffles. Both lateral and longitudinal excitations were applied to the truck model. It was observed that the presence of baffles has negligible effect on the lateral slosh force and the corresponding resonant frequency. However, baffles caused a significant increase in the longitudinal mode resonant frequency. The effect of numbers and size of sections on longitudinal slosh using baffles was studied by Wang, Rakheja, and Sun (1995), and division of tank into equal sections was recommended to reduce longitudinal load during straight line braking. Quasi-static model limited to fluid slosh in the steady state was employed in this investigation.

Most of the studies discussed above were carried out on cylindrical tanks. Shape of the container, and fill level of the liquid are also key factors that determine stability of a vehicle against sloshing, and efforts have been made to address these. For lateral accelerations in the range of .1–1 g, elliptical containers of aspect ratio (height to width ratio) in the range of .35–.625 have been found to be most suitable (Popov, Sankar, & Sankar, 1996). Stability of a vehicle is generally defined in terms of ‘static rollover threshold’, expressed as lateral acceleration in gravitational units (g). Passenger cars have static rollover threshold above 1 g. For light trucks, SUVs and vans, the threshold lies in the range of .8 g–1.2 g. However, for heavy-duty tankers, this value decreases to .5 g, but can go down to .17 g at high speeds and under certain manoeuvres (e.g. lane change or turning), which makes them susceptible to rollover (Winkler & Ervin, 1999). Various tank shapes with different fill levels were studied by Rakheja, Sankar, and Ranganathan (1989) to compare the stability of various geometric shapes. It was concluded that rollover threshold is strongly related to the tank cross-section geometry. Reduction in fill level from 83 to 34% decreased the threshold from .38 to .35 g. The modified square tank was found to be stable than elliptical and circular tanks. Although lateral sloshing was studied, the effect of baffles on tanker stability was not evaluated in this study.

Panigrahy, Saha, and Maity (2009), conducted experiments in a rectangular tank and concluded that sloshing of a fluid decreases with increasing height. They also identified ring baffles (a combination of vertical and horizontal baffles) to be more effective at damping compared to the conventional horizontal baffles. The effect of size and location of baffle orifice on the slosh has been reported for rectangular (Popov, Sankar, & Sankar, 1993) and a generic (Guorong & Rakheja, 2009) cross-section tank. Popov et al. (1993) on studying the effect of size and location of the orifice of a transverse baffle reported that an orifice opening equal to 5% of the baffle area would yield a 29% increase in the peak overturning moment for a fill depth ratio of 70%, compared to a separating wall. Comparable magnitudes of slosh forces and moments have been reported for orifice opening ranging from 8 to 20% of the cross-section area (Guorong & Rakheja, 2009). Sloshing in a tanker is influenced by its geometry (shape and size), fill level, fluid properties, type of manoeuvre being experienced and the baffle configuration used inside the tank. The effect of fluid properties in rollover stability has been reported by Ali, Kamran, Majid, and Khan (2013).

It is clear from the discussion above that introduction of baffles reduces the brake failure in heavy tanks. Although some studies have focused on understanding lateral sloshing, the literature is devoid of a detailed analysis of lateral sloshing, and the effect of baffles for different tank geometries for various fill levels. The current study extends the previous studies in the literature by introducing new tank's shapes that correspond to maximum rollover stability as compared to the already available standard tank designs. The study reported here investigated three most commonly used tank geometries i.e. circular, elliptical and modified rectangular. Fluid sloshing under right lane change manoeuvre was investigated for tank fill levels (in terms of height of container) of 30–90% with an increment of 20%. Four different baffle configurations horizontal (H), vertical (V), diagonal (D) and vertical–horizontal (VH) baffles were considered. For all configurations, three different baffles lengths, corresponding to l/a (l is the length of baffle, 'a' is the radius in the direction of orientation of the baffle) ratios of .25, .5 and .75 were examined. The objective of this investigation was to study and analyse numerically, the effectiveness of different baffle configurations and tanker's shapes in limiting the manoeuvre-induced lateral fluid slosh forces and moments.

2. Computational techniques and procedures

The numerical modelling in the current study was performed using CFD-ACE+. The numerical modelling procedure started with the development of scaled geometries of circular, elliptical and modified (mod) rectangular tanks as shown in

Figure 1. Selection of tank geometries was based on the work of Sanker and Sanker (1993); the dimensions are listed in Table 1.

Free VOF method that was first proposed by Hirt and Nicholas (1981) was employed to model the two-phase flow in the current study. VOF model is a surface-tracking technique designed for two or more immiscible fluids where position of the interface between the fluids such as a gas and a liquid, is of interest. Ability of the method in modelling multiphase flows is well documented (Santhanam, 2014).

In VOF, the relative mixture of the two fluids within the problem domain is tracked in terms of the volume fraction, F, of one of the two fluids, and the approximate interface shape is reconstructed through interpolation. Given a flow field and an initial distribution of F, the volume fraction distribution F evolves is determined by solving the passive transport equation (Hirt & Nichols, 1981; Kandasamy, Rakheja, & Ahmed, 2010).

$$\frac{\partial F}{\partial t} + \nabla . VF = 0 \tag{1}$$

where F is the liquid volume fraction, t is time, ∇ is the standard spatial gradient operator and $\mathbf{V}$ is the velocity vector. This equation is solved with the fundamental equations of conservation of mass and momentum in CFD-ACE+ to achieve computational coupling between the velocity field solution and the liquid distribution. The proportions of fluid one and fluid two in the mixture, together with the properties of these fluids, determines the average density, viscosity, etc., in a given computational cell. In particular, the average value of any volume-specific quantity ϕ, in a computational cell can be computed from the value of F in accordance with

$$\tilde{\phi} = F\phi_2 + (1 - F)\phi_1 \tag{2}$$

where $\tilde{\phi}$ is the volume-averaged quantity, ϕ_1 is the value of the quantity for fluid one (air) and ϕ_2 is the value of the property for fluid two (water). For the sake of completeness, the continuity and momentum equations solved in conjunction with the VOF equation are listed below.

$$\text{Continuity equation:} \qquad \nabla . \left(\rho \vec{V} \right) + \frac{\partial \rho}{\partial t} = 0 \tag{3}$$

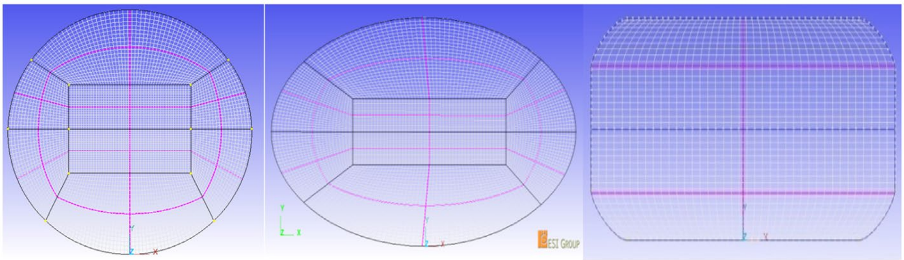

Figure 1. Solution domain and mesh for circular, elliptical and mod-rectangular Tank.

Table 1. Dimensions of tank geometries modelled.

Tank Shape	Major radius (m)	Minor radius (m)	Area (m^2)
Elliptical	1.38	0.69	2.99
Circular	1.38	1.38	5.98
Mod-Rectangular	1.38	0.69	3.81

$$x\text{ - momentum:} \qquad \nabla.\left(\rho u\vec{V}\right)+\frac{\partial \rho u}{\partial t}=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y} \tag{4}$$

$$y\text{ - momentum:} \qquad \nabla.\left(\rho v\vec{V}\right)+\frac{\partial \rho v}{\partial t}=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y} \tag{5}$$

The VOF method was implemented using an upwind scheme with piecewise linear interface construction (PLIC) and thus minimising the possibility of formation of tiny isolated droplets of liquid in gas regions, and of bubbles of gas in liquid regions(flotsam and jetsam). Two phases of fluids were specified in the model. Air was selected as the primary phase fluid, while water was selected as secondary phase fluid. A structured mesh with quadrilateral elements supported by PLIC was used as shown in Figure 1. The mesh consisted of approximately 6000 cell nodes; the exact number of cells varied from case to case. Four different fill levels of 30, 50, 70 and 90% in terms of vertical height were modelled. The mesh density was kept nearly consistent to ensure the uniformity of results obtained. The grid dependency study was performed, shown in Figure 2. The solution becomes almost constant as the grid density was increased beyond the fine grid size.

To simulate the constant radius turn, a constant lateral acceleration of .3 g was applied in the lateral (x) direction. The simulations were run for 10seconds to

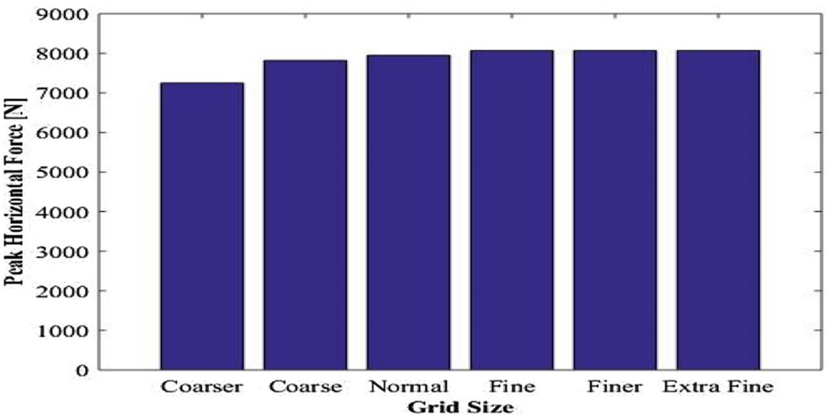

Figure 2. Grid dependence test.

study the transient behaviour of fluid. Response of the system to applied excitation was analysed in terms of dynamic horizontal forces acting on the walls of the container, and dynamic pressure moments acting at the centre of the base of the container. An in-house code in MATLAB was developed to extract the required data from the raw output file generated by CFD-ACE+. Validation of the employed methodology for the different fill levels was done against the work of Tanugula (2002), Figure 3. A comparison of coefficient of moments ($C_M = M_{\text{max}}/M_{\text{mean}}$) and coefficient of force ($C_F = F_{\text{max}}/F_{\text{mean}}$)shows that CFD-ACE+ model was in good agreement with the Fluent model used by Tanugula (2002)and was able to replicate the decreasing trend in C_M and C_F with an increase in fill level. Since the objective was to carry out a comparative study, therefore, results of the relative effect of baffles on sloshing can be taken with a high degree of confidence.

3. Results and discussions

Before discussing the effect of different baffle configurations employed in the present study, simulations for the clean (without baffles) tank geometries were carried out. The anti-slosh effectiveness of baffles was evaluated by determining effect of baffles on the dynamic horizontal force acting on the wall, and dynamic pressure moment acting at the centre of the base of the container. Figure 4 showing the time history of these variables for the modified rectangular tank at a fill level of 50% illustrates that both parameters invariably behave in the same manner, and either of these two can be used for comparison purposes. Similar behaviour was noted for all tank geometries and fill levels.

Besides the sloshing frequency (which can cause resonance), amplitude of the pressure moments is of prime concern to the designer for safe operations. Figure 5 showing the peak pressure moments at different fill levels for the tank geometries illustrates that the circular tank geometry is the least stable for the applied manoeuvre, since the peak moment increases with an increase in fill level for the circular geometry. However, for the modified-rectangular geometry, the peak

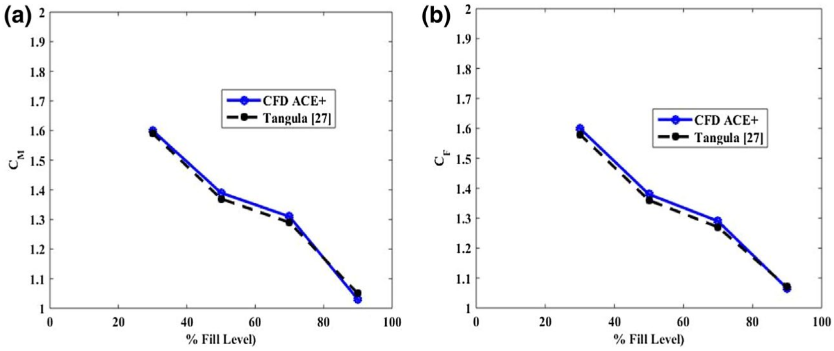

Figure 3. Comparison of dynamic coefficient of (a) Moment (C_M), (b) Force (C_F).

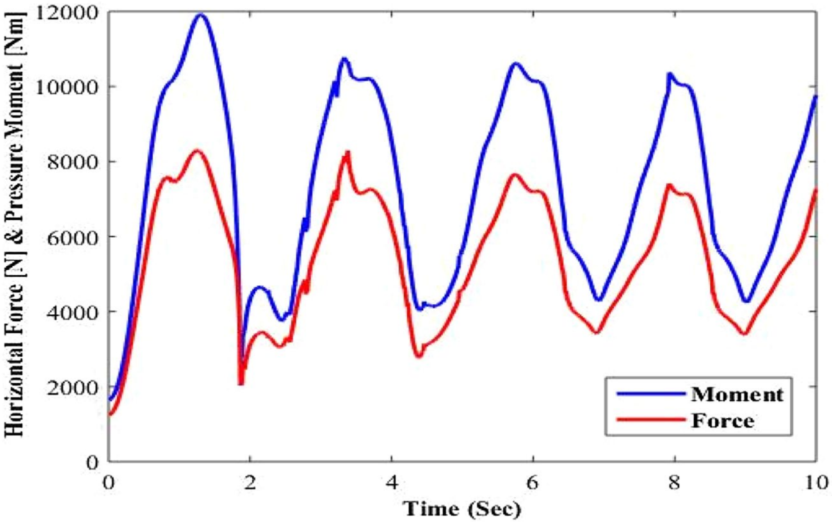

Figure 4. Time-histories of dynamic forces and moments for 50% fill level (Modified Rectangular).

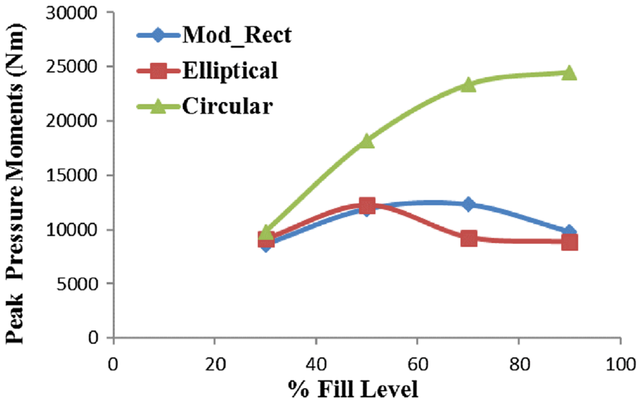

Figure 5. Effect of fill level on peak pressure moments (Without Baffles).

moment can be seen at a fill level of 70%, and then a downward trend is noted. Although the mass of fluid increases with increment in the fill level beyond 70% for the tank, the space available for the fluid to slosh reduces e.g. magnitude of the peak pressure moments at fill levels of 30 and 90% is almost the same. Sloshing pattern for the elliptical tank shows the peak at 50%, with sloshing at 70% fill almost the same as 30% exhibiting a sharper decrease beyond 50%. It can be inferred from Figure 4 that the critical fill level for maximum sloshing lies between 50 and 70% for the elliptical and modified rectangular tanks, depending on the aspect ratio of the geometry. Similarity in the behaviour of elliptical and modified rectangular tanks (in terms of a distinct peak) is due to the two geometries being of the same aspect ratio as sloshing behaviour depends on both, shape and size of the tanks.

The difference in magnitudes can be attributed to the different volumes of the fluid contained at the same fill levels due to difference in geometries (Table 1).

These clean tank values in Figure 5 will serve as the baseline case for comparison purposes, when baffles are introduced. The following section discusses the effect of introduction of the different baffle lengths and types on tank.

3.1. Modified rectangular tank

For the modified rectangular tank, the effect of horizontal (H), vertical (V), vertical–horizontal (VH) and diagonal (D) baffles on sloshing was investigated. All baffle configurations were placed at the centre of the tank (in the given orientation) except the diagonal baffles which were placed at the corners of the tank (Figure 6). It is also important to note here that only two horizontal and vertical baffles were introduced at a time, while in the vertical–horizontal and diagonal arrangements, four baffles were required.

3.1.1. Horizontal baffles (H)

As discussed above, baffles with three different aspect ratios (.25, .5 and .75) were studied at fill levels of 30, 50, 70 and 90%. Figures 7 and 8, shows the variation of pressure moments under the influence of horizontal baffles of different lengths at

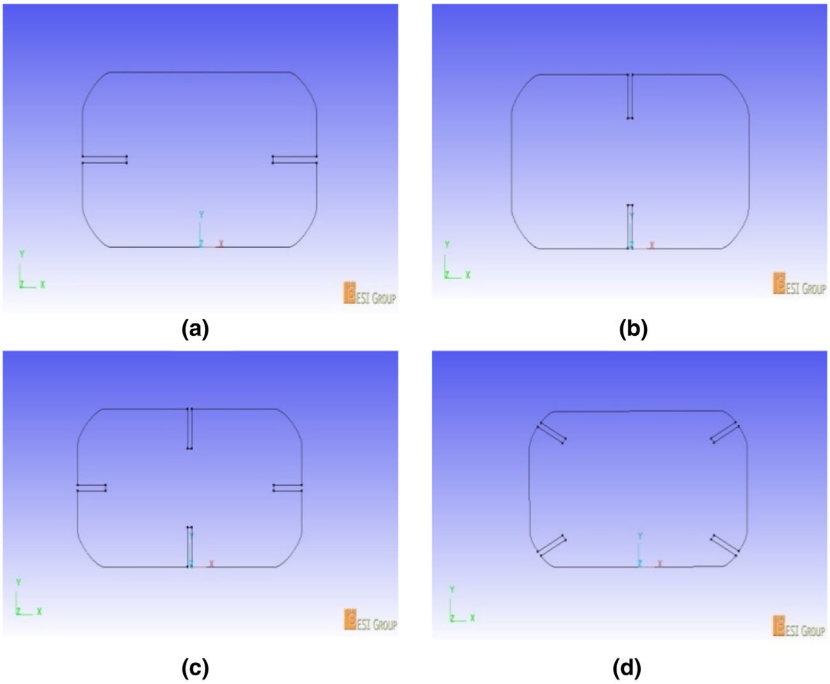

Figure 6. Modified rectangular tank with different baffle configurations (a) Horizontal, (b) Vertical, (c) Vertical–horizontal, (d) Diagonal.

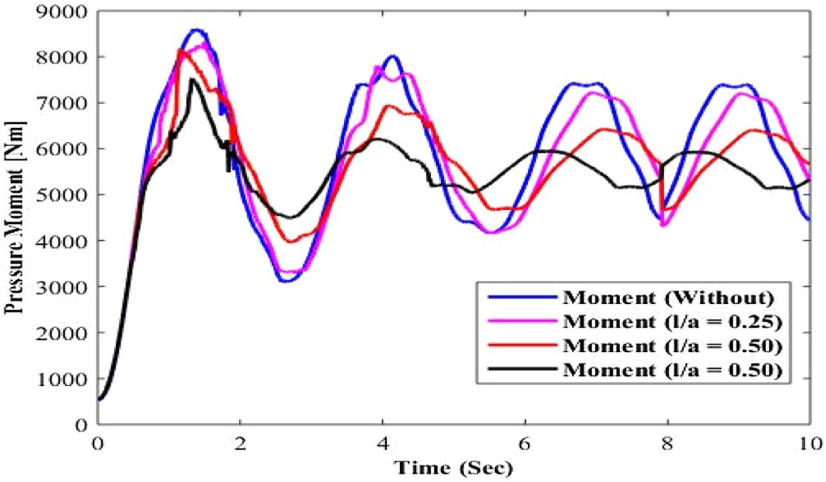

Figure 7. Time-histories of pressure moments at 30% fill level (Modified Rectangular) for different aspect ratios (l/a) (Horizontal Baffles).

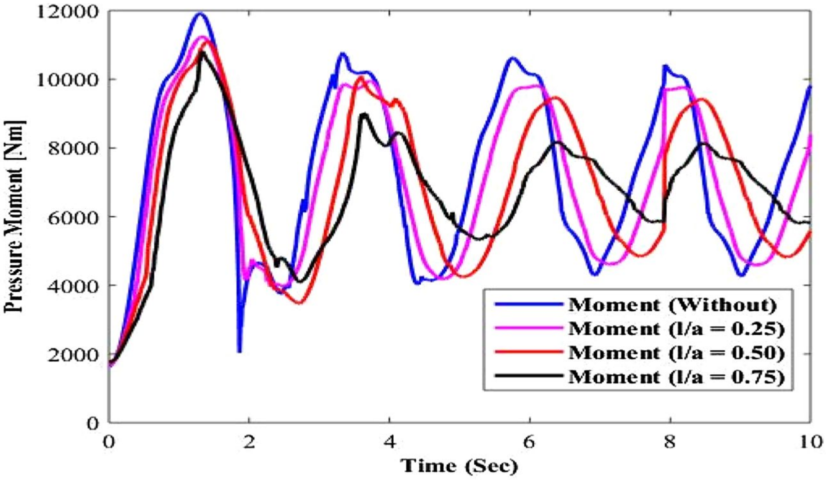

Figure 8. Time-histories of pressure moments at 50% fill level (Modified Rectangular) for different aspect ratios (l/a) (Horizontal Baffles).

fill levels of 30 and 50%, respectively. These baffles were able to reduce the pressure moments and their effectiveness increases with an increase in length of the baffle. Due to its larger length, the horizontal baffle with aspect ratio of .75 caused the largest decrease in the pressure moments. Also notable is that the damping effect of baffles is more pronounced during the second and third sloshing cycles, due to portions of the fluid being trapped under the baffles. The presence of baffles not only diminishes the peak pressure moment but also yields lower steady values due to portions of fluid being trapped in lower section of the tank.

To elaborate the effect of horizontal baffles, further peak values of pressure moments for all the fill levels are shown in Figure 9. There is a huge effect of the baffle's length of the pressure moments. It can be seen in Figure 8 that with an aspect ratio (1/a) of .25, the pressure moment has still a higher value of the pressure moments. However, as the baffle length is increased, the horizontal baffle caused a decrease in the moments with the l/a = .5 and l/a = .75 baffles almost equally effective, making l/a = .5 an optimal length. Comparing the relative effectiveness of baffles for the 50 and 70% fill levels, the horizontal baffles were much more effective at the lower fill level of 50%, since they were stationed at the free surface of the fluid, not allowing the fluid covered by the baffles to strike the wall. Sloshing in the container is a function of both, the volume (mass) of fluid in the container as well as the space available for the fluid to vibrate (slosh). At 90% fill level, there is very little space for the fluid to slosh and introduction of baffles does not affect the pressure moments significantly; hence the magnitude of peak moments remains invariably the same for all the baffle lengths.

3.1.2. Vertical baffles (V)

Figure 10 showing the pressure moments at a fill level of 70% illustrates that baffle lengths up to l/a = .5 had very little effect on the pressure moments compared to the clean case. However, at an aspect ratio of .75, the pressure moment variation looks very similar to that of horizontal baffles shown in Figure 8. The relative ineffectiveness at shorter baffle lengths was due to the complete immersion of the lower baffle within the fluid, and very little interaction of the top baffle with the fluid contained inside the tanker. However, as the length increased, the vertical baffles acted as compartments restricting the flow on the left of the container to strike the walls, except from the space between the two baffles as shown in Figure 11. It can be seen in Figure 12 that at the lower fill level of 30%, all the baffles caused a significant reduction of the pressure moments and even the shorter lower baffle was able to control the fluid movement. A glance at Figure 13 further elucidates the

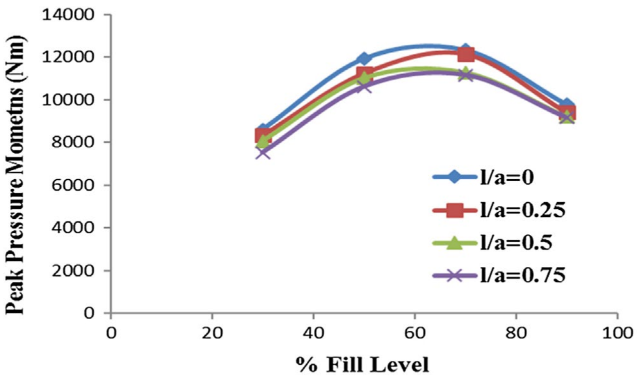

Figure 9. Comparison of peak pressure moments in modified rectangular tank with horizontal baffles at fill levels of 30, 50, 70 and 90%.

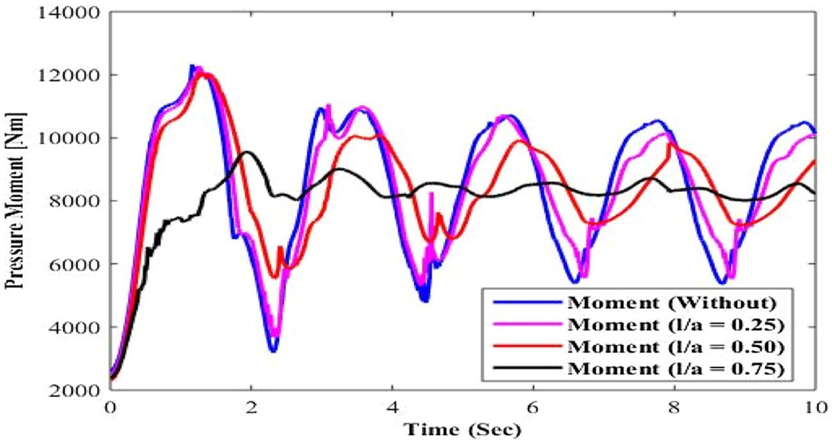

Figure 10. Time-histories of pressure moments at 70% fill level (Modified Rectangular) for different aspect ratios (Vertical Baffles).

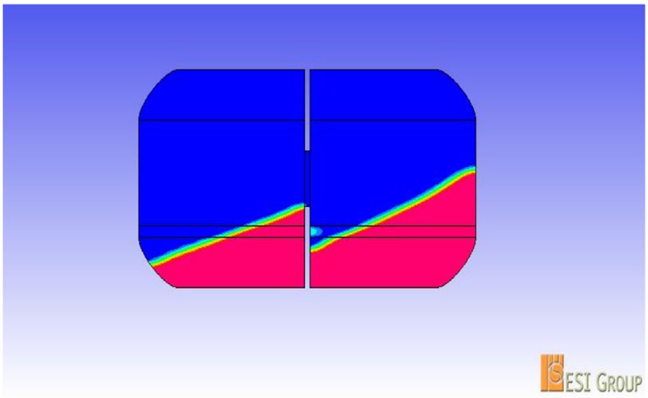

Figure 11. Volume fraction of fluid in 30% fill tanks with vertical baffles (1/a = 0.75).

superior performance of the largest baffle (l/a = .75) in reducing the fluid sloshing at all fill levels, especially for the technically relevant 50 and 70% fill levels. Also, a comparison of Figure 13 with Figure 9 clearly identifies the vertical baffles to be more effective in reducing sloshing compared to the horizontal baffles. Since the reduction in pressure moments due to horizontal and vertical baffles was caused by different phenomenon, a combination of the two configurations was also simulated to investigate the extent of any additional advantage. The results are discussed next.

3.1.3. Vertical–Horizontal baffles (VH)

Figure 14 shows that the pressure moments at 70% fill level does not show a significant reduction in magnitudes under the influence of vertical–horizontal baffles compared to Figure 10 (showing effect of vertical baffles only for the same

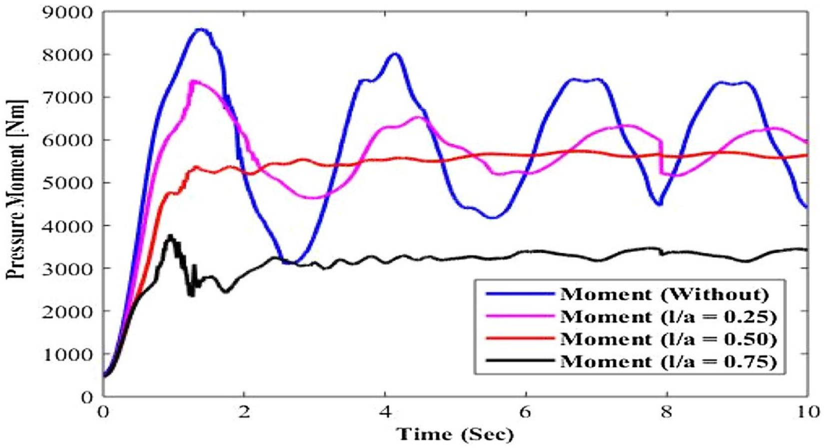

Figure 12. Time-histories of pressure moments at 30% fill level (Modified Rectangular) for different aspect ratios (Vertical Baffles).

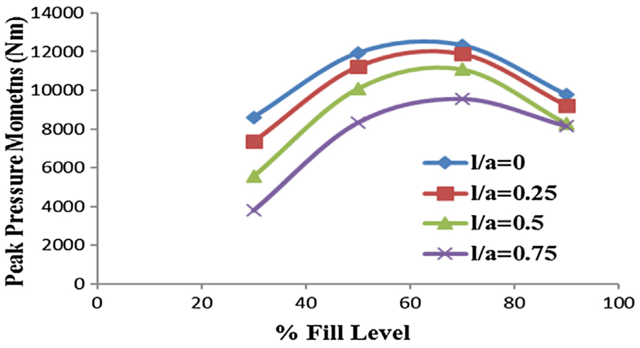

Figure 13. Comparison of peak pressure moments in modified rectangular tank with vertical baffles at fill levels of 30, 50, 70 and 90%.

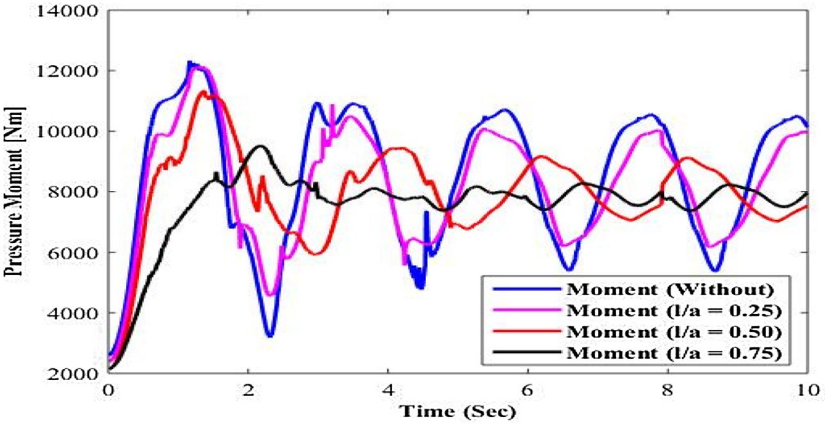

Figure 14. Time-histories of pressure moments at 70% fill level (Modified Rectangular) for different aspect ratios (Vertical–Horizontal Baffles).

fill level). Looking closely, the only notable difference exists for vertical–horizontal baffle with aspect ratio of .50, which was slightly more effective in reducing the pressure moments compared to the vertical baffle.

A comparison of the per cent reduction in peak pressure moments due to vertical and vertical–horizontal baffles is presented in Figure 15. Clearly, at a fill level of 50% the vertical–horizontal combination is more effective in reducing the sloshing for all baffle lengths. A maximum additional reduction of up to 6% is visible for the longest baffle. This additional reduction can be attributed to the free surface effect, since the horizontal baffle sits on the free surface of the fluid, restricting the movement of the trapped fluid. Another notable advantage is also visible at a fill level of 30%, with the horizontal baffle stopping the flow underneath to strike the walls of the tank. However, at 70% fill level, the vertical–horizontal baffle does not cause any further reduction compared to the vertical baffle, and application of this configuration cannot be justified. Hence for the rectangular tank, the vertical baffles appear to be the optimal configuration.

3.1.4. Diagonal baffles (D)

The final baffle configuration investigated in the study was designed to determine if an inclined baffle at the corners of the tank will be better at restricting the fluid movement compared to the horizontal and vertical configurations. However, the results in Figure 16 shows that despite being twice in number compared to vertical baffles, the diagonal baffles were significantly less effective at reducing sloshing. Hence, the diagonal baffle orientation was not considered for other tank geometries investigated, which are discussed next.

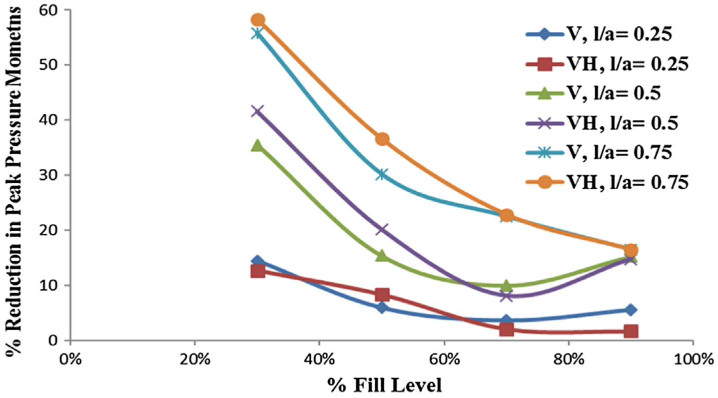

Figure 15. Per cent reduction in peak pressure moments in modified rectangular tank with vertical and vertical–horizontal baffles at fill levels of 30, 50, 70 and 90%.

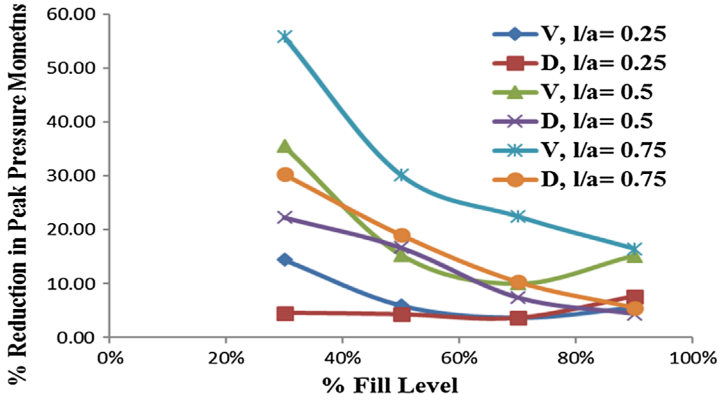

Figure 16. Per cent reduction in peak pressure moments in modified rectangular tank with vertical and diagonal baffles at fill levels of 30, 50, 70 and 90%.

3.2. Elliptical tank

Similar to the modified rectangular tank, the effect of horizontal (H), vertical (V) and vertical–horizontal (VH) baffles on sloshing was investigated for the elliptical tank. The findings are presented below.

3.2.1. Horizontal baffles (H)

Figures 17 and 18 shows the variation of pressure moments under the influence of horizontal baffles of different lengths at fill levels of 50 and 70%, respectively. At a fill level of 50%, there is a small effect of the changing baffle length on pressure moments during the first two cycles but during the third cycle, the effect of

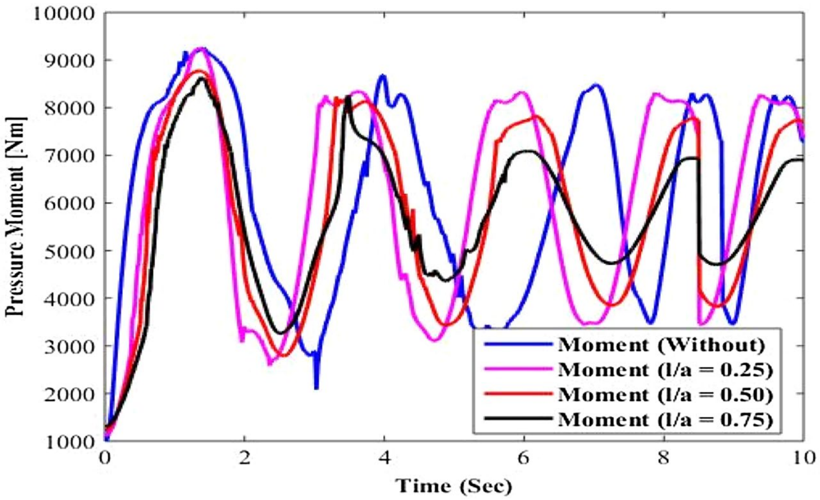

Figure 17. Time-histories of pressure moments at 50% fill level (Elliptical) for different aspect ratios (Horizontal Baffles).

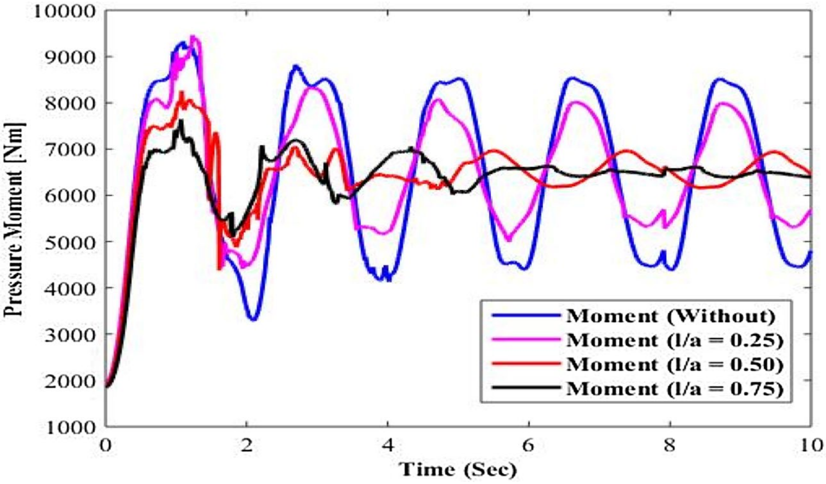

Figure 18. Time-histories of pressure moments at 70% fill level (Elliptical) for different aspect ratios (Horizontal Baffles).

larger baffles is much more pronounced. However, changing baffle lengths had an immediate effect at a fill level of 70% as shown in Figure 18 with Horizontal baffles at an aspect ratio of .75 is the best at reducing sloshing. Figure 19 showing peak pressure moments, illustrates that introduction of horizontal baffles in the elliptical and modified rectangular geometries have similar effects. A reduction of 15% in the peak pressure moments was noted at the critical fill level as shown in Figure 5 of 50% with the Horizontal baffles at an aspect ratio of .75, while a maximum reduction of 19% was observed at 70% fill level. Corresponding values for the modified rectangular tank of 10 and 9%, respectively depicts that horizontal baffles are slightly better at reducing sloshing in elliptical tanks.

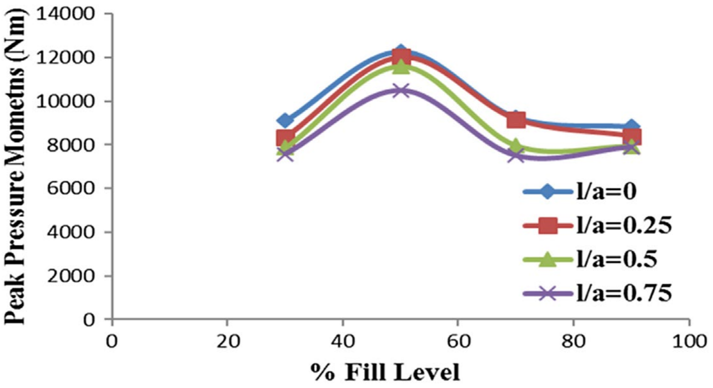

Figure 19. Comparison of peak Pressure moments in elliptical tank with horizontal baffles at fill levels of 30, 50, 70 and 90%.

3.2.2 Vertical baffles (V)

Introduction of vertical baffles had a similar effect on the elliptical tank as noted for the modified rectangular tank. At a fill level of 50%, the vertical baffle at an aspect ratio of .75 was considerably better at restricting the fluid to strike against the wall compared to the vertical baffle at an aspect ratio of .50 as shown in Figure 20. Also, notable in Figure 20 is that the vertical baffle has an immediate effect on pressure moments, visible during the first cycle contrary to the horizontal baffles where the effect of baffle became apparent during the third cycle. Figure 21 showing the pressure moments at 70% fill level also indicates that the vertical baffle at an aspect ratio of .75 has significantly reduced the sloshing. To compare the relative effectiveness of all baffles, peak pressure moments are plotted in Figure 22 for all fill levels. Maximum reductions of 26 and 25% were noted at fill levels of 50 and 70%, respectively with the vertical baffle at an aspect ratio of .75 configuration. These results illustrate that vertical baffles are significantly better than horizontal baffles at reducing lateral sloshing for both the modified rectangular and elliptical geometries.

3.2.3 Vertical–Horizontal baffles (VH)

Effect of introduction of the additional two horizontal baffles along with the vertical baffles presented in Figure 23 reveals that the vertical–horizontal baffle configuration caused significant reduction in peak pressure moments at technically relevant fill levels of 50 and 70% for aspect ratios of .50 and .75 compared to a slight reduction observed for the modified rectangular geometry as shown in Figure 15. This is primarily due to the elliptical curvature; walls of the tank are located closer to the fluid compared to the modified rectangular tanks. Introduction of the horizontal baffles stops the fluid underneath to strike the wall, in addition to the

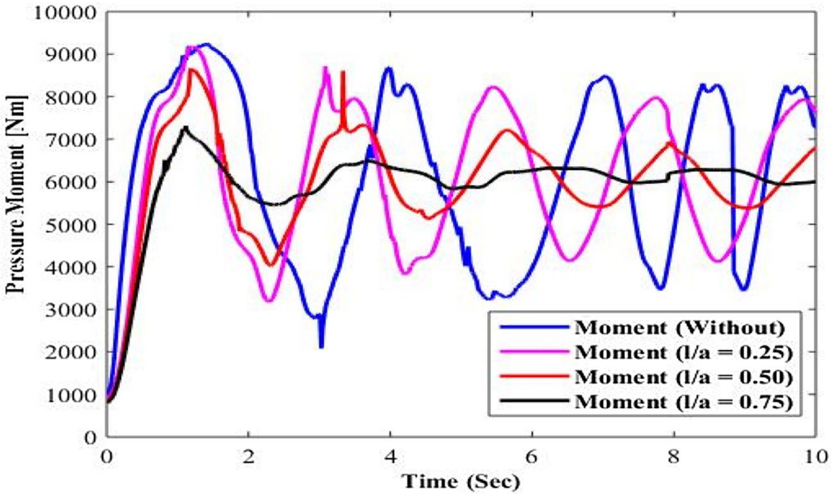

Figure 20. Time-histories of pressure moments at 50% fill level (Elliptical) for different aspect ratios (Vertical Baffles).

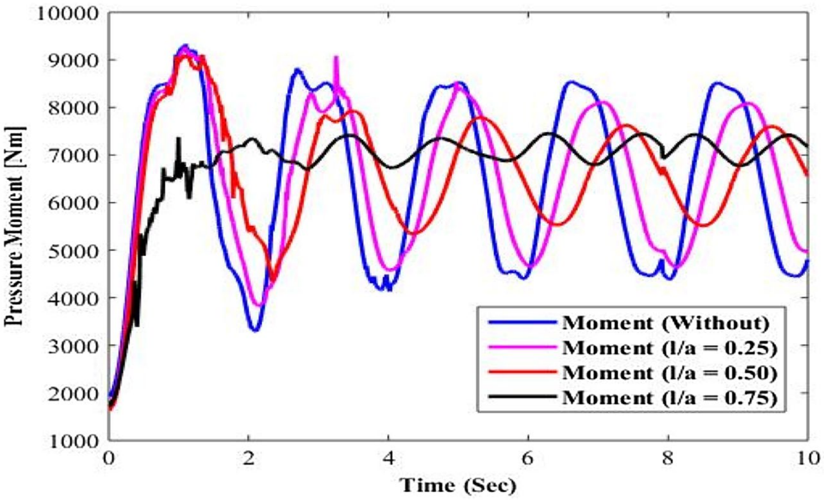

Figure 21. Time-histories of pressure moments at70% fill level (Elliptical) for different aspect ratios (Vertical Baffles).

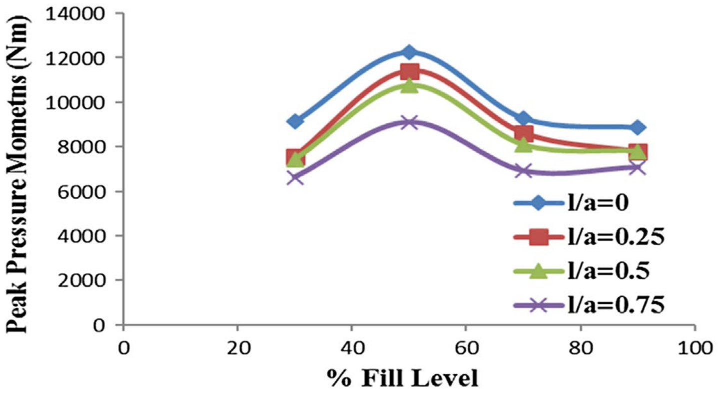

Figure 22. Comparison of peak pressure moments in elliptical tank with vertical baffles at fill levels of 30, 50, 70 and 90%.

vertical baffles restricting the fluid movement laterally. Hence, the vertical–horizontal configuration is more effective in the elliptical tank. Maximum reductions of 35% noted at fill levels of 50 and 70% demonstrate that vertical–horizontal baffle configuration is a viable option for controlling sloshing in elliptical tanks.

3.3. Circular tank

Finally, sloshing response of horizontal (H), vertical (V) and vertical–horizontal (VH) baffles investigated for the circular tank is presented.

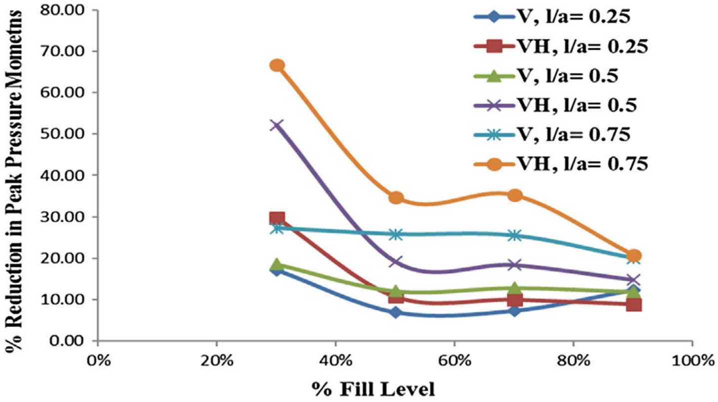

Figure 23. Reduction in peak pressure moments in elliptical tank with vertical and vertical–horizontal baffles at fill levels of 30, 50, 70 and 90%.

3.3.1. Horizontal baffles (H)

Introduction of horizontal baffles did not result in any notable reduction of the peak pressure moments, except at a fill level of 50% as shown in Figure 24. A cursory look at Figure 25 showing time history of pressure moments would further strengthen this conclusion, as the baffles were not able to disturb the pressure moment pattern significantly, even at a fill level of 30%. This inability of the horizontal baffles at reducing sloshing can be attributed to the larger VOF contained in the circular tank compared to the elliptical tank. Since sloshing is a function of the VOF, the sloshing effects continue to increase with an increase of volume, with the horizontal baffles providing very little resistance. As mentioned above, a notable exception to this can be seen at a fill level of 50% as shown in Figure 24. The baffle sits on the free surface of the fluid stopping any movement of the fluid, producing the same effect as that of a fully filled container. Clearly, as the baffle

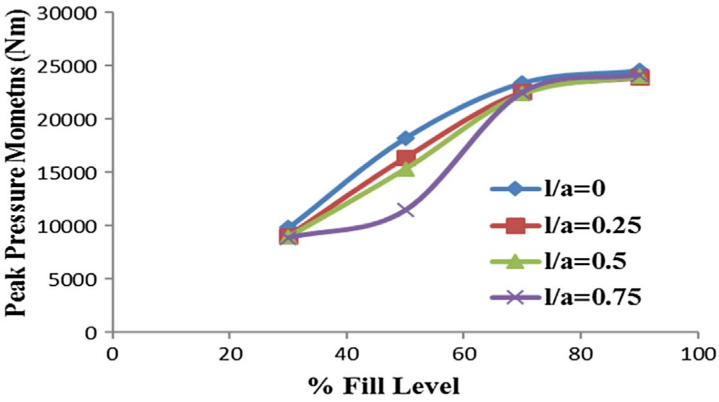

Figure 24. Comparison of beak pressure moments in circular tank with horizontal baffles at fill levels of 30, 50, 70 and 90%.

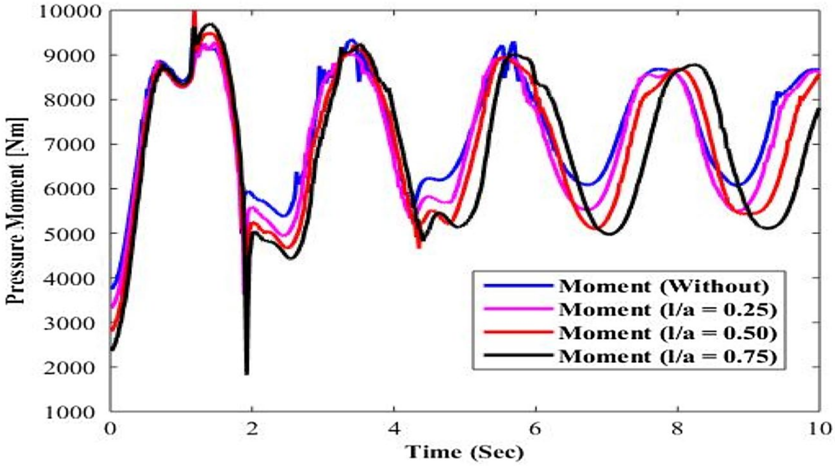

Figure 25. Time-histories of pressure moments at 30% fill level for different aspect ratios (Horizontal Baffles).

length is increased, this effect spreads over a much larger area, causing reduction in the peak pressure moments.

3.3.2. Vertical baffles (V)

A glance at Figures 26 and 27 showing the peak pressure moments at fill levels of 50 and 70%, respectively shows that the vertical configuration was much more effective at reducing sloshing compared to the horizontal baffles. A closer look will identify only the vertical baffles at an aspect ratio of .75 at reducing the moments, while the vertical baffles at an aspect ratio of .50 generally remains ineffective. This is because the vertical baffles at an aspect ratio of .50 are located

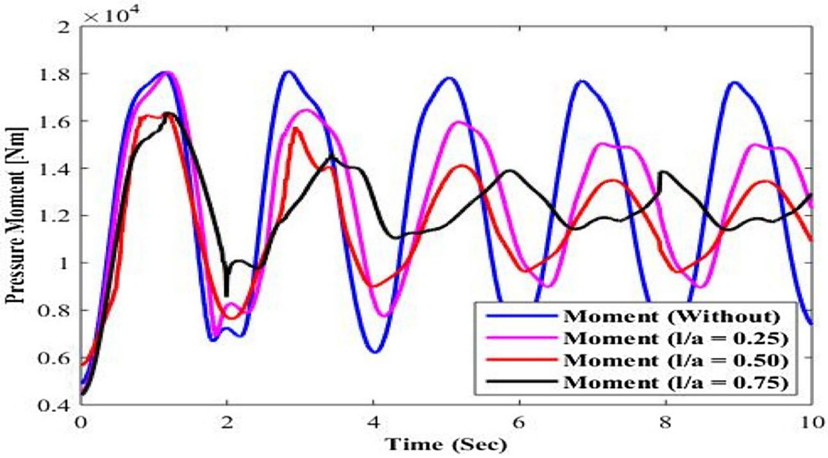

Figure 26. Time-histories of pressure moments at 50% fill level for different aspect ratios (Vertical Baffles).

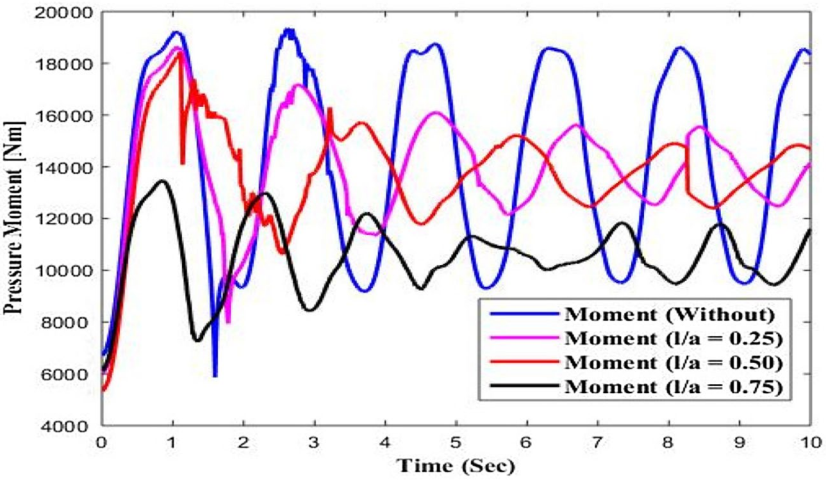

Figure 27. Time-histories of pressure moments at70% fill Level for different aspect ratios (Vertical Baffles).

far away from the free surface of fluid, and hence it is unable to disturb the flow significantly. However, some effect of the vertical baffles at an aspect ratio of .50 can be seen during the second and third sloshing cycles. This effect can also be identified from Figure 28, showing the peak pressure moments, where a maximum reduction of 25% was observed at a fill level of 75% for the vertical baffles at an aspect ratio of .75.

3.3.3. Vertical–Horizontal baffles (VH)

Similar to the elliptical tank, the introduction of additional two horizontal baffles along with the vertical baffles had a significant effect on sloshing. For aspect ratio of .5, effect of the additional horizontal baffles are only visible at a fill level

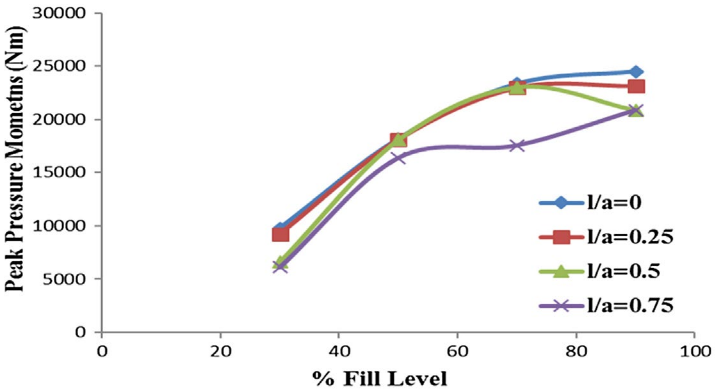

Figure 28. Comparison of peak pressure moments in circular tank with vertical baffles at fill levels of 30, 50, 70 and 90%.

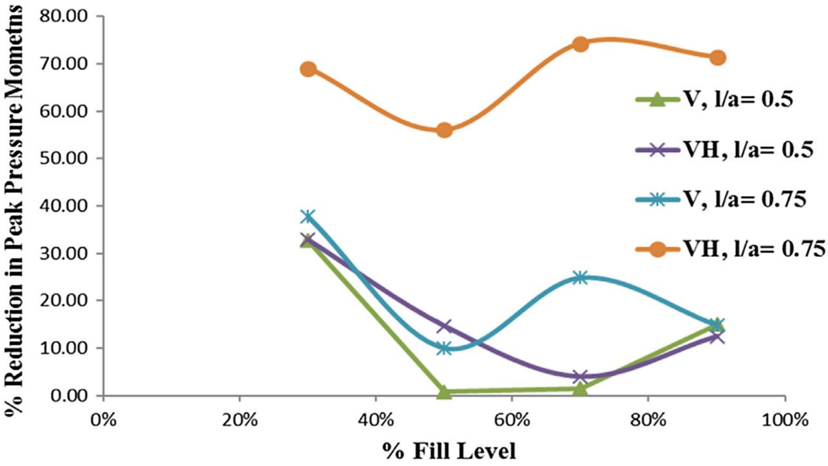

Figure 29. Per cent reduction in peak pressure moments in circular tank with vertical and vertical–horizontal baffles at fill levels of 30, 50, 70 and 90%.

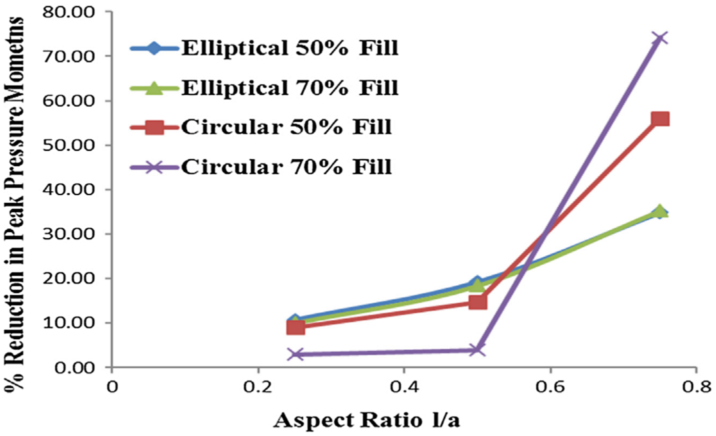

Figure 30. Per cent reduction in peak pressure moments in circular tank with vertical and vertical–horizontal baffles at fill levels of 30, 50, 70 and 90%.

of 50% due to the wall boundary effect. However, as the baffle length is increased corresponding to an aspect ratio of .75, the horizontal baffles serve to reduce the sloshing considerably compared to the vertical baffles only as shown in Figure 29. Since a similar effect was also observed for the elliptical tank, a comparison of the effectiveness of vertical–horizontal configuration in elliptical and circular tanks is presented in Figure 30. At an aspect ratio of .5, the vertical–horizontal configuration is almost equally effective for 50% filled circular and elliptical tanks. However, this baffle length was not able to reduce sloshing for the 70% filled circular tank. As the aspect ratio was increased to .75, an increase in baffle effectiveness was observed for both the tanks. However, the effect of vertical–horizontal configuration is much more pronounced in the circular tank. This is due to the limited inter-baffle spacing in the circular tank due to larger length of the vertical baffle compared to the elliptical tank.

4. Conclusions

The objective of this investigation was to study and analyse numerically, the effectiveness of different baffle configurations in limiting the manoeuvre-induced lateral fluid slosh. Sloshing in a tanker is influenced by its geometry (shape and size), fill level, fluid properties, type of manoeuvre being experienced and the baffle configuration used inside the tank. Sloshing phenomenon, under the effect of constant radius turn was studied for the modified rectangular, elliptical and circular geometries at different fill levels, for different baffle configurations. Fill levels in the range of 50–70% were identified to be the most critical, where the amplitudes of pressure moments and horizontal forces were maximised for the modified rectangular and elliptical geometries. However, for circular geometry, an increase in sloshing was noted with an increase in fill levels.

For all tank geometries, the horizontal baffle was most effective at reducing sloshing at a fill level of 50%, when the baffle sat on top of the free surface of fluid, while the vertical baffles were much more effective than the horizontal baffles at controlling the lateral slosh. Also, in general, longer baffles were found to be better at controlling the pressure moments for all the configurations studied. Specifically, for the modified rectangular geometry, vertical baffles were found to be optimal in terms of reducing sloshing, although the vertical–horizontal configuration gave slightly higher reductions. The vertical–horizontal configuration in elliptical and circular geometries was significantly better at controlling pressure moments compared to the vertical baffle configuration e.g. maximum reductions of 35% were noted at fill levels of 50 and 70% in the elliptical geometry. This effect was even more pronounced in the circular tank, which makes the vertical–horizontal baffle configuration a viable option for these tank geometries.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Abramson, H. N., & Silverman, S. (1966). The dynamic behavior of liquids in moving containers (Report No. NASA-SP-106). San Antonio, TX: Southwest Research Institute (US).

Ali, S., Kamran, A., Majid, A., & Khan, S. (2013). Effect of fluid physical properties on rollover stability in terms of damping of dynamic forces & moments in fluid sloshing. *International Journal of Advanced Research in Engineering and Technology, 4*(3), 286–295.

Aliabadi, S., Andrew, J., & Jalal, A. (2003). Comparison of finite element and pendulum models for simulation of sloshing. *Computers & Fluids, 32*(4), 535–545.

Ballinger, I. A., Lay, W. D., & Tam, W. H. (1995, July). Review and history of PSI elastomeric diaphragm tanks. In *31st AIAA/ASME/SAE/ASEE joint Propulsion Conference and Exhibit*, San Diego, CA.

Blower, D., & Pettis, L.. *Trucks involved in fatal accidents*. Codebook 2001 (Technical Report UMTRI-98-14). Ann Arbor, MI: University of Michigan Transportation Research Institute.

Blower, D., & Pettis, L. *Trucks involved in fatal accidents*. Codebook 2002 (Technical Report UMTRI-99-18). Ann Arbor, MI: University of Michigan Transportation Research Institute.

Cho, J. R., Lee, H. W., & Ha, S. Y. (2005). Finite element analysis of resonant sloshing response in 2-D baffled tank. *Journal of Sound and Vibration, 288*(4-5), 829–845.

Gosta, A. (1981). The Los Alfaques disaster: A boiling liquid, expanding vapor explosion. *Burns, 7*(4), 233–251.

Guorong, Y., & Rakheja, S. (2009). Straight-line braking dynamic analysis of a partly-filled baffled and un-baffled tank truck. *International Journal of Automotive Technology, Automotive Engineering, 223*(1), 11–26.

Hirt, C. W., & Nicholas, B. D. (1981). Volume of fluid method for the dynamics of free boundaries. *Journal of Computational Physics, 39*(1), 201–225.

Hirt, C. W., & Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics, 39*(1), 201–225.

Kandasamy, T., Rakheja, S., & Ahmed, A. K. W. (2010). An analysis of baffles designs for limiting fluid slosh in partly filled tank trucks. *The Open Transportation Journal, 4*, 23–32.

Klaus, L. (2002, June 16–20) Tanker trucks in the current accident scene and potentials for enhanced safety, GDV, Institute for safety, Leopoldstr. *7th international symposium on heavy vehicle weights and dimensions*, Munich, Germany.

Modaressi-Tehrani, K., Rakheja, S., & Sitharu, I. (2007). Three-dimensional analysis of transient slosh within a partly-filled tank equipped with baffles. *Vehicle System Dynamics, 45*(6), 525–548.

Panigrahy, P. K., Saha, U. K., & Maity, D. (2009). Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks. *Ocean Engineering, 36*(3), 213–222.

Popov, G., Sankar, S., & Sankar, T. S. (1993). Dynamics of liquid sloshing in baffled and compartmented road containers. *Journal of Fluids and Structures, 7*(7), 803–821.

Popov, G., Sankar, S., & Sankar, T. S. (1996). Shape optimization of elliptical road containers due to liquid load in steady-state turning. *Vehicle System Dynamics, 25*(3), 203–221.

Rakheja, S., Sankar, S., & Ranganathan, R. (1989). *Influence of Truck Design Factors on the Rollover Threshold of Partially Filled Tank Vehicles* (SAE Technical paper No. 892480).

Rayleigh, J. W. S. L. (1876). On waves. *Philosophical Magazine Series 51*, 257–279.

Sanker, S., & Sanker, T. (1993). Dynamics of liquid sloshing in baffled and compartmented road containers. *Journal of Fluids and Structures, 7*(7), 803–821.

Santhanam, V. (2014). *Slosh Damping With Floating Magnetoactive Micro-Baffles* (M.Sc dissertation). Embry-Riddle Aeronautical University, Daytona Beach, FL.

Silveira, M. A., Stephens, D. G., & Leonard, H. W. (1961). *An experimental investigation of the damping of liquid oscillations in cylindrical tanks with various baffles*. Washington, DC: National Aeronautics and Space Administration.

Staebler, R. The safety chain for carriage of dangerous goods on street, duty or cure? *VDI Report No. 1617*, Nutzfhrzeug-Tangung, Neu-Ulm, 2001.

Stofan, A. J., & Sumner, I. E. (1963, June). *Experimental investigation of the slosh-damping effectiveness of positive-expulsion bags and diaphragms in spherical tanks*. Ohio: Lewis Research Center Cleveland.

Tanugula, R. (2002, April). *Stability analysis of partially filled tanker trucks using a finite element modeling approach* (Master's thesis). West Virginia University.

Wang, Z., Rakheja, S., & Sun, C. (1995, November). Influence of partition location on braking performance of a partly filled tank truck. *Proceedings of the SAE Truck & Bus Meet & Expo*. Winston-Salem, NC. Paper no. 952639.

Winkler, C. B., & Ervin, R. D. (1999). Rollover of heavy commercial vehicles. *UMTRI Research Review, 31*(4), 1–23.

Yan, G., & Rakheja, S. (2009). Straight-line braking dynamic analysis of partly-filled baffled and un-baffled tank truck. *International Journal of Automotive Technology, Automotive Engineering, 223*(1), 11–26.

Yan, G., Rakheja, S., & Siddiqui, K. (2009). Experimental study of liquid slosh dynamics in a partially filled tank. *Journal of Fluids Engineering, 131*(7), 071303.