Analysis of perforated fixed baffle at low filling ratio to reduce sloshing using SPH

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Abstract. Prismatic tanks are used widely in various industrial applications, including marine and petroleum, due to their ease in design and storage capacity. However, these tanks often experience sloshing issues that can affect vessel stability. Sloshing effects can cause undesirable motions and impact the system's overall performance. This study focuses on analyzing the effect of perforated shapes on fixed baffles as a solution to reduce the sloshing effect in prismatic tanks. Baffle or anti-sloshing is an internal partition used to minimize the movement of liquid in the tank. The analysis method uses Smoothed particle hydrodynamics (SPH), which is a particle method or can be referred to as mesh-free computational fluid dynamics. The parameters tested include the perforated shape and the filling ratio of the water filling in the tank. The analysis found that the perforated form of the baffles has a significant effect on reducing the sloshing effect. The perforated shape of the fixed baffles has the same impact on reducing the sloshing effect of the prismatic tank. There is no significant difference in the ability of each baffle shape to overcome the sloshing problem. The findings from this study can guide designers or engineers in designing prismatic tanks that are more stable and reduce the effects of sloshing. Using baffles with the right perforated shape can optimize tank performance in maritime and shipping.

Keywords: Sloshing, Stability, Perforated, Baffle, SPH

1. Intoduction

Sloshing can be defined as the free motion of a liquid fluid in a container. The sloshing problem is an important phenomenon in fluid motion analysis because it can cause damage to the structure in the frame. Sloshing in tanks is affected by tank size, tank shape, tank type, liquid level, excitation frequency, and anti-sloshing. The impact of sloshing can be prevented by minimizing the motion of fluid motion with the use of anti-sloshing or baffles [1].

A baffle is an additional structure in the tank that is used to reduce the flow of water movement in the tank [2]. Perforated baffles in sloshing tanks are usually made of metal plates with arranged small holes. Baffles or anti-sloshing are structures installed inside the tank to control sloshing or wave motion that occurs when the tank is filled with liquid and experiences sudden acceleration or deceleration. It can cause stability and balance problems. In Choun and Yun's research [3], the effect of the size and location of baffles on rectangular tanks on sloshing resulted in a reduced sloshing frequency with the addition of baffles.

The holes in the perforated baffle allow the liquid to flow in a restricted manner between the compartments, reducing the free motion of the liquid and excessive sloshing effects. Since sloshing events in tanks are related to free surface motion, meshless methods have the advantage used in sloshing cases because there is no mesh that the nonliniear phenomenon is easily captured. As a relatively new mesh-free numerical computing method, SPH (smoothed particle hydrodynamics) is often associated with solving free surface problems such as sloshing models with the fully Lagrangian particle method [4].

The works on SPH in free surface flow were first conducted by Monaghan [5]. Since that research, there have been many applications of SPH in free surface flow. The works conducted by Monaghan et al. [6] for multi-phase flow simulation on SPH. Dalrymple and Rogers [7] conducted research using SPH in modeling water waves. Crespo et al. [8] examined the efficiency and reliability of GPU as a tool in accelerating SPH simulation. The goal of this research is to analyze the perforated fixed baffle at a low filling ratio in order to reduce the sloshing problem using SPH. Trimulyono et al. [9] established a 25% filling ratio for the sloshing experiment. One pressure sensor near a free surface was validated using the results of an experiment.

Furthermore, the hydrodynamic force and free surface deformation with and without a baffle have been compared. SPH was calculated utilizing vertical and horizontal baffles. DualSPHysic version 5.0, an open-source SPH solver, was utilized in this study [10]. The SPH simulation in this work was rendered using VisualSPHysics. VisualSPHysics is a Blender add-on that allows SPH simulation and advanced processing [11]. SPH is advanced post-processed using Blender version 2.92. Much research on sloshing has been conducted, but only a few have employed sophisticated techniques to render CFD findings. The findings showed that SPH could reproduce dynamic pressure and that baffles successfully mitigated the sloshing phenomena.

2. Methodology

2.1 Smoothed Particle Hydrodynamics (SPH)

SPH is a meshless Lagrangian procedure that uses a discrete evaluation point interpolation scheme to estimate physical values and derivatives of continuous fields. These assessment points have been defined as particles with mass, velocity, and position values. These values are computed as a weighted average of neighboring particles within a rarefaction length h to limit the range of contributions from distant particles. Liu and Liu [12] explain the main features of the SPH approach, which is based on integral interpolants. In SPH, the integral approximation can be used to approximate the field function *A(r)* in a domain *Ω*, resulting in the particle approximation shown in equation (1), where W is the kernel function and $\boldsymbol{r}$ is a position vector. The Navier Stokes governing equation is shown in equation (3), where $\boldsymbol{v}$ is velocity, P is pressure, ρ density, $\boldsymbol{\tau}$ and is a diffusive term.

$$\boldsymbol{A(r_a) \approx \sum_b A(r_b) W(r_a - r_b, h) \frac{m_b}{\rho_b}} \quad (1)$$

$$\frac{D\rho}{Dt} = -\rho\nabla v, \quad (2)$$

$$\frac{Dv}{Dt} = -\frac{1}{\rho}\nabla P + g + \tau, \quad (3)$$

$$\boldsymbol{\frac{Dr}{Dt} = v}, \quad (4)$$

The quintic kernel function [10] is utilized in this study, as shown in equation (5). The momentum equation can be seen in Equation (6). Because of the work of Molteni and Colagrossi [11], the delta-SPH (_) appears in equation (7), and the continuity equation becomes equation (7). Equation (8) illustrates the state equation.

$$\boldsymbol{W(q) = \alpha_D \left(1 - \frac{q}{2}\right)^4 (2q+1) \quad 0 \le q \le 2} \tag{5}$$

$$\frac{dv_a}{dt} = -\sum_b m_b \left(\frac{P_{a+P_b}}{\rho_a \cdot \rho_b} + \Pi_{ab}\right) \nabla_a W_{ab} + \mathbf{g}, \tag{6}$$

$$\text{where } \Pi_{ab} = \begin{cases} \frac{-\alpha \overline{c_{ab}} \mu_{ab}}{\overline{\rho_{ab}}} & v_{ab} \cdot r_{ab} < 0 \\ 0 & v_{ab} \cdot r_{ab} > 0 \end{cases},$$

$$\frac{d\rho_a}{dt} = \sum_b m_b v_{ab} \cdot \nabla_a W_{ab} + 2\delta_\Phi h c_0 \sum_{b(\rho_b - \rho_a)} \frac{r_{ab} \cdot \nabla_a W_{ab}}{r_{ab}^2} \frac{m_b}{\rho_b} \tag{7}$$

$$P = b\left[\left(\frac{\rho}{\rho_0}\right)^\gamma - 1\right] \tag{8}$$

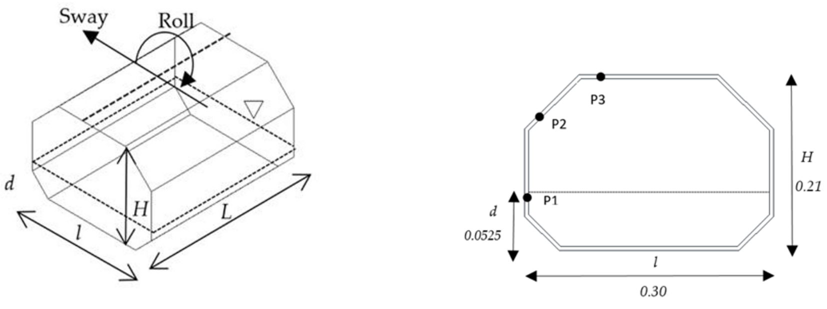
2.2 Experimental Setup

Based on Trimulyono et al., [9], a prismatic tank was utilized to simulate a membrane LNG carrier compartment for the sloshing experimental condition. The pressure sensor is located in the middle of the tank. Dynamic pressure was measured compared to SPH. The conditions of the 25% filling ratio sloshing experiment are shown in Figure 1. In this work, sloshing at low filling ratios was only replicated using a 25% filling ratio. Low filling ratio scenarios resulted in more dangerous sloshing than other filling ratio scenarios because they increased the violentness of the fluid movement and increased the possibility of excessive motion inside the ship compartment. For liquid carriers such as LNG carriers, it is crucial to prevent sloshing at low filling ratios. Figure 1 displays the prismatic tank sketch for the SPH simulation. Rolling motion was used to replicate sloshing in low filling ratios. Similar to the manner in which the pressure sensor in the experiment was fixed during sloshing, the SPH simulation used a similar configuration. The rolling motion of the tank throughout the experiment is shown in Figure 2, and the SPH setup likewise used this similar movement. There is an external frequency stimulation of 1.04 Hz and a motion amplitude of 8.66°. A prismatic tank's natural frequency, 1.10 Hz at a 25% filling ratio, is fairly close to this frequency. The natural frequency of the prismatic tank was calculated using Equations (1) and (2) [13]. Where *l* is the length of the free surface in the tank's movement direction, d is the height of the water, and n is the frequency of the *i*-natural mode for a rectangular tank. For a prismatic tank with a chamfered bottom, the horizontal and vertical chamfer diameters are denoted by δ1 and δ2, respectively. Please see Ref. [9] for more information on the sloshing experiment.

$$\omega_n = \sqrt{\frac{i\pi g \tanh\left(\frac{i\pi d}{l}\right)}{l}} \tag{11}$$

$$\frac{\omega_n'^2}{\omega_n^2} = 1 - \frac{\delta_1 \delta_2^{-1} \sinh\left(\frac{\pi i \delta_2}{l}\right) - \delta_1 \delta_2^{-1} \left(\sin\left(\frac{\pi i \delta_1}{l}\right)\right)^2}{\pi \sin h\left(\frac{2\pi i d}{l}\right)} \tag{12}$$

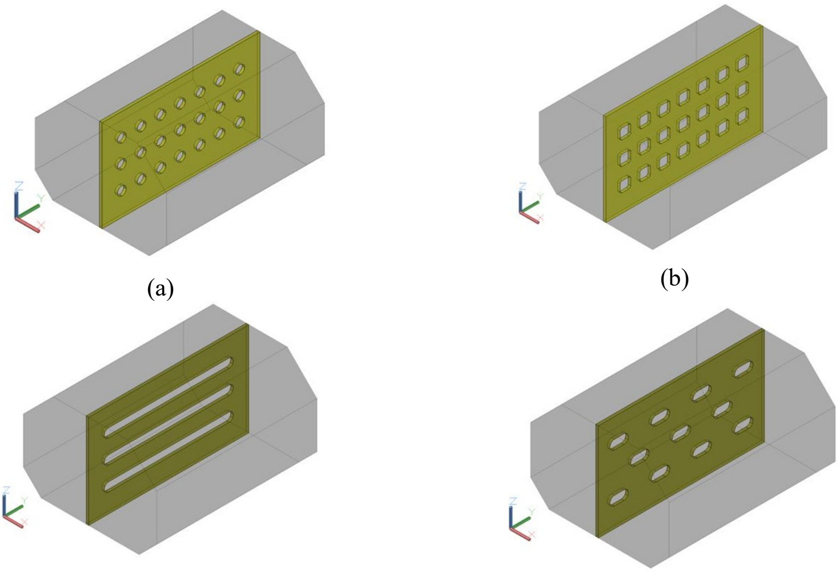
Figure 1 shows a 3D and 2D sketch of the prismatic tank. The tank's width is 0.3 m, its height is 0.21 m, and its water depth is 0.0525 m for a 25% filling ratio. In comparison to the experiment, only the bottom pressure sensor (P1) was used. Particles settle after two seconds in the SPH simulation addition time simulation. This extra time was also used to calculate static pressure, which was compared to an analytical solution.



(a)

(b)

Figure 1. The sketch of prismatic tank in SPH in 3D (a) and 2D (b).



(a)

(b)

(c)

(d)

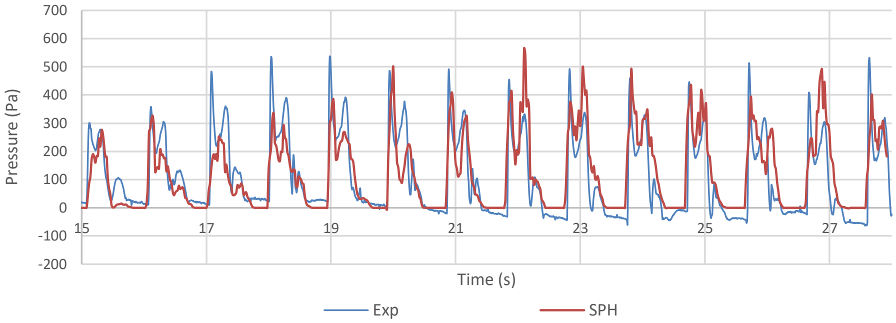
Figure 2. Variations of Perforated Baffle (a) [B1] Circle Perforated Baffle (b) [B2] Square Perforated Baffle (c) [B3] Oblonggated Perforated Baffle (d) [B4] Oblonggated Patterned Perforated Baffle

3. Results and Discussions

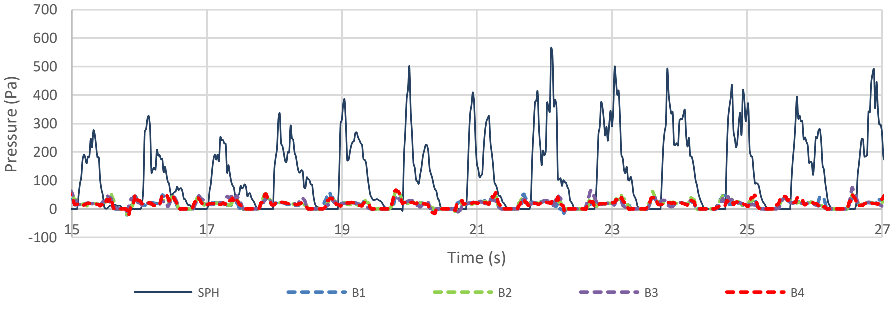
3.1 Dynamic Pressure

The dynamic pressure simulation results in SPH have involved validation with experiments previously conducted on a prismatic tank without baffles [9]. Comparison of the experimental results with the SPH simulation results reveals that the difference between the two is only about 2%, indicating a high degree of agreement between the simulation and experimental results [9]. These results indicate that the SPH method is effective in simulating the sloshing phenomenon in prismatic tanks, and the simulation results are reliable as a tool that can be used in research on the effect of perforated baffles on reducing sloshing. Figure 3 shows the comparison between experimental results and SPH, which supports the validity of the SPH simulation method used in this study. Validation is done by comparing the dynamic pressure in a prismatic tank without baffles between experiments and SPH. One effective way to reduce sloshing is the use of baffles. Past research has observed that vertical baffles effectively reduce sloshing in square tanks, as do perforated fixed baffles [14]. The use of baffles is effective in overcoming sloshing, especially in reducing pressure according to the configuration and location of the baffle [2].

The shape of the perforated fixed baffle that proved most effective in reducing the dynamic pressure caused by the sloshing phenomenon was the square perforated baffle (B2). The study revealed that the use of a square perforated baffle (B2) resulted in a remarkable pressure reduction, reaching 87%. However, all perforated baffle shapes exhibited similar pressure reduction characteristics. Despite the differences in shape and design, the results show that there is no significant pressure difference between the various perforated baffle shapes. Figures 4 show a view of the pressure distribution in the tank during a sloshing event. It can be seen that the dynamic pressure occurs in the area affected by the baffle as a pressure reducer in the sloshing event.

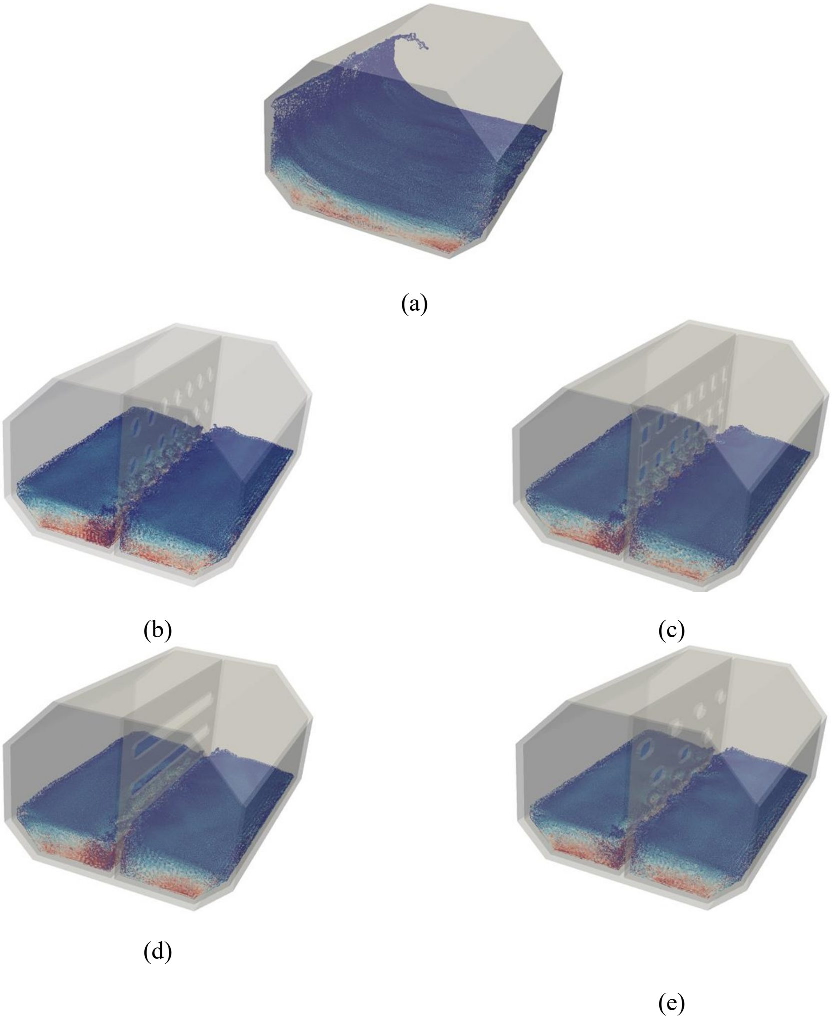


(a)



(b)

Figure 3. Comparison of dynamic pressure (a) for SPH and experiment , (b) for SPH and Perforated Baffle



(a)

(b) (c)

(d)

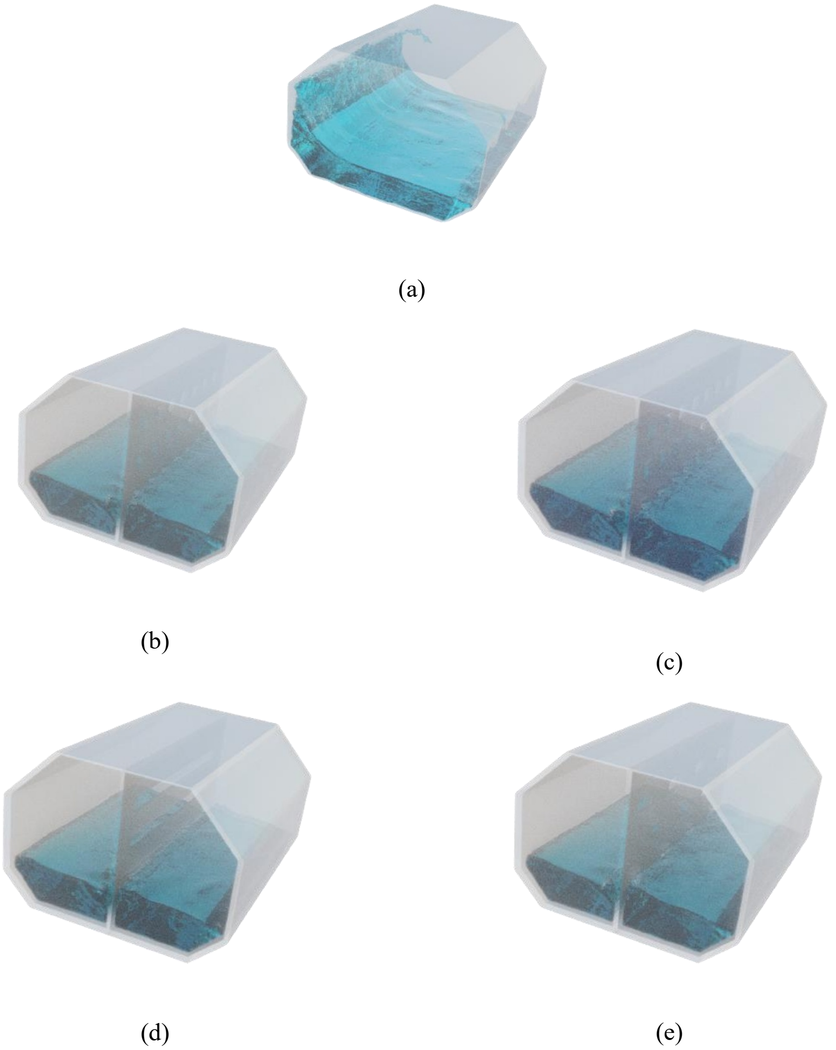
(e)

Figure 4. Pressure contour of dynamic pressure (a) without baffle, (b) Circle Perforated Baffle [B1], (c) Square Perforated Baffle [B2], (d) Oblonggated Perforated Baffle [B3], and (e) Oblong Patterned Perforated Baffle [B4].

3.2 Free Surface Deformation

Blender 2.92 was used to perform the free surface deformation of sloshing in the prismatic tank in order to increase visualization. VisualSPHysics has made advanced post-processing visualization easier to perform; the fluid has far more appealing texturing than isosurface or particle form. It shows that there is no wave formed and that the vertical baffle efficiently inhibits fluid movement.

Free surface deformation using VisualSPHysics is shown in Figure 5 with and without a baffle. The results indicated that waves caused by sloshing could be reduced using a baffle. A vertical baffle caused the fluid to settle, and Table 1 shows comparable results. When the fluid is created with VisualSPHysics, it resembles real fluid more realistically. The results show that one of the merit particle techniques is superior to mesh-based CFD. Particle techniques such as SPH will be widely used in research and entertainment in the future. To observe the impact of the combination of water and air in Table 1. The height sensor in the water level simulation is divided into two parts: first, "center", which is the point between the baffle and the edge of the tank side; second, "side", which is the edge of the tank side.



(a)

(b) (c)

(d) (e)

Figure 5. Free surface deformation of sloshing (a) without baffle, (b) Circle Perforated Baffle [B1], (c) Square Perforated Baffle [B2], (d) Oblonggated Perforated Baffle [B3], and (e) Oblong Patterned Perforated Baffle [B4].

Table 1. Mean of Peak Water Wave Height and Percentage Decrease

Variable	Mean of peak water wave height Filling ratio 25% (m)	
	Center	Side
No Baffle	0,118	0,138
B1	0,066 (44%)	0,076 (45%)
B2	0,066 (44%)	0,075 (45%)
B3	0,066 (44%)	0,077 (44%)
B4	0,066 (44%)	0,076 (45%)

3.3 Hydrodynamic Force

The A constant oscillatory force causes the hydrodynamic force in the tank during the sloshing period. The tank is given a roll motion as a constant external oscillatory force, resulting in a hydrodynamic force on the tank.

A comparison of the results of the force graph in the simulation of tank sloshing with baffles using SPH can be seen in Figure 6. The effect of baffles on the tank can suppress the force results from sloshing, but not as effective compared to dynamic pressure as in the simulation results. In the simulation of a 25% SPH filling ratio tank without baffles, the peak average value was reached with a result of 11.8 N. The use of perforated fixed baffles can overcome the force of sloshing by approximately 11% on all baffles.

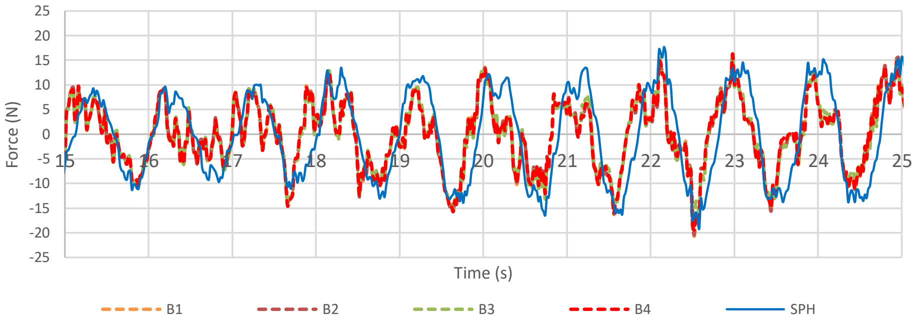


Figure 6. Comparison of Hydrodynamic Forces on each Perforated Baffle

4. Conclusions

The sloshing phenomenon in a prismatic tank with a 25% filling ratio is reproduced and analyzed using Smoothed Particle Hydrodynamics (SPH). Dynamic pressure data from the SPH simulation were validated and showed good accuracy.The way the perforated fixed baffle on the tank varies indicates that has a significant impact on the sloshing problem in the simulation results of the roll with a 25% filling ratio. There is a reduction of 87% in dynamic pressure, 44% in wave height, and 11% in hydrodynamic force.

The findings demonstrate that the reduction of the sloshing effect on prismatic tanks is influenced by the difference in perforated shape on fixed baffles. The capacity of each baffle form to solve the sloshing issue varies not significantly. As a result, choosing the best baffle shape should take into account a variety of factors, including the manufacturing process, the baffle's strength under sloshing, and other factors, in addition to the baffle's capacity to reduce the phenomenon of sloshing.

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