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Investigation of Sloshing with Vertical and Horizontal Baffle in the Prismatic Tank using Meshfree CFD

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ABSTRACT

Sloshing is a phenomenon where the tank experiences an external oscillating motion due to the interaction of fluid with tank. The most appropriate way to prevent instability from the sloshing movement is to add baffles or anti-sloshing. This paper was conducted with the 3D simulation of sloshing roll motion on the prismatic tank with a simulation time of 28 seconds. Vertical and Horizontal baffles were used to mitigate sloshing in the prismatic tank. The ratio of baffle height and water depth is 0.7, 0.8 and 0.9. Moreover, horizontal baffle position is 0.1, 0.2, 0.3, and 0.4 respectively, with the tank filling water ratio is 25%. The numerical study was carried out using meshfree CFD, i.e., Smoothed Particle Hydrodynamics. In addition, advanced post-processing was conducted with Blender. The aims of this study were found out the effective baffle configuration to reduce sloshing using vertical and horizontal in the prismatic tank. The results showed the most effective baffle variation for roll motion is 0.9 for vertical baffle and a horizontal baffle height is 0.1 from the water surface. It showed baffles effectively reduces dynamic pressure, hydrodynamic force and free surface deformation.

1. Introduction

Sloshing is one of the natural phenomena of liquid carriers due to external excitation to the tank, that there is a free surface inside tank because the tank is not fully loaded. Many studies have been conducted to perform sloshing in numerical methods, and experiments to understand and made mitigation of damage caused by sloshing. Numerical method has developed rapidly due to computer technology development in the late decade. Numerical methods for instance computational fluid dynamics (CFD) has widely used to solve free surface flow. CFD has been wide uses to solve free surface flow not only sloshing but also medical [1, 2], marine engineering [3, 4], mechanical engineering [5-7], Numerical study of floating breakwater was performed with CFD for calculation of transmission coefficient value [8]. Because free surface flow dealing with large discontinuities and deformation, meshfree CFD is suitable to apply. One of major meshfree CFD i.e. smoothed particle

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hydrodynamics (SPH) that developed for free surface by Monaghan [9]. SPH is a meshfree and Lagrangian method because there is no need to generate mesh as results large deformation and discontinuities easy to capture. SPH was introduced a decade ago, but studies have shown that it is a promising approach for free surface flow.

The application of CFD for sloshing in the rectangular tank using two-phase CFD was carried out in OpenFOAM [10]. Sloshing simulation in rectangular tank was performed using Coupled Level Set and Volume Of Fluid (CLSVOF) [11]. Sway-sloshing in rectangular tank with baffle was performed in mesh based CFD OpenFOAM [12]. Using Arbitrary Lagrangian Euler method sloshing in 3D tank was carried out with experimental validation [13]. A resonant sloshing couples with heave and surge excitations was performed in rectangular tank [14]. Single and double vertical baffles are used to reduce sloshing in the rectangular tank [15]. Parametric studies of different water depths, excitation frequencies, and baffle heights by a cartesian grid method using prismatic tank was carried out by Jin *et al.,* [16]. The study of T-shape baffles was conducted in laminar and turbulence finite volume method by Ünal *et al.,* [17]. The compressible VOF was performed to validate sloshing induced-phenomenon in rectangular tank [18]. It was found that CFD is one of major solution in sloshing showed good accuracy for solving free surface flow.

The application of meshfree CFD or well-known as particle method for sloshing in prismatic tank was conducted with two-phase SPH [19]. Sloshing in prismatic tank with baffle was performed in SPH with advanced post-processing [20, 21]. To mitigate sloshing in the tank an elastic baffles are used with coupling Smoothed Finite Element method [22]. Coupled SPH and SPIM was performed to study sloshing with elastic baffles and clamped plate [23]. Long duration sloshing in different shape compartment was conducted with δ-SPH [24]. Furthermore, coupled δ-SPH with the smoothed finite element method (SFEM) was carried out by Zhang *et al.,* [25]. Long-time simulation of sloshing in LNG tanks recently carried out by Pilloton *et al.,* [26].The study shows SPH one of particle method that has a good accuracy for capture discontinuities and large-deformation.

The purpose of this study is to perform a numerical investigation of sloshing in prismatic tank with SPH. The sloshing experiment was based on Trimulyono *et al.,* [27]. i.e., 25% filling ratio. An experiment result was used to verify one pressure sensor that was close to a free surface. Furthermore, a comparison of the hydrodynamic force and free surface deformation with and without a baffle was made. The vertical and horizontal baffles were used in SPH computation. In this study, DualSPHysic version 5.0, an open-source SPH solver, was employed [28]. In this paper, VisualSPHysics was used to render the SPH simulation. VisualSPHysics is add on in Blender that SPH simulation can be imported and advanced processing could be carried out [29]. Blender version 2.92 is used to perform advanced post-processing on SPH. There have been many studies on sloshing, but only a small number are used advanced techniques to render CFD result. The results indicated SPH could reproduced dynamic pressure and baffles are effectively mitigating the sloshing phenomenon.

2. Methodology

2.1 Experimental Setup

A prismatic tank was used to represent a membrane LNG carrier compartment for the experimental condition of sloshing, which was based on Trimulyono *et al*., [27]. Pressure sensor location is at mid of tank, and dynamic pressure was captured then comparison made with SPH. Figure 1 illustrates the condition of sloshing experiment of filling ratio 25%, in this paper only filling ratio of 25 % was used to reproduce sloshing in the low filling ratio. Sloshing became more hazardous in low filling ratio situations compared to other filling ratio situations because it made fluid movement more violent and giving rise to the risk of excessive motion in the ship compartment. Due to this, avoiding sloshing in low filling ratios is important for liquid carriers like LNG carriers. The prismatic tank sketch for SPH simulation is shown in Figure 1. Sloshing with in low filling ratio was reproduced by rolling motion. In the experiment, the pressure sensor was fixed during sloshing, a similar setup was employed in the SPH simulation. Figure 2 depicts the rolling motion of the tank during the experiment, the same movement was also employed in the SPH configuration. The amplitude of motion is 8.66°, with an external frequency stimulation of 1.04 Hz. This frequency is quite similar to a prismatic tank's natural frequency, which is 1.10 Hz for a 25% filling ratio. The prismatic tank's natural frequency was calculated using Eq. (1) and (2) [30]. Where n is the *i*-natural mode's frequency for a rectangular tank, *d* stands for the water's height, and *l* for the free surface's length in the direction of tank movement. For a prismatic tank with a chamfered bottom, *δ1* and *δ2* are the chamfer's horizontal and vertical dimensions, respectively. Please refer to Ref. [27] for further information in detail on the sloshing experiment.

$$\omega_n = \sqrt{\frac{i\pi g tanh\left(\frac{i\pi d}{l}\right)}{l}} \quad (1)$$

$$\frac{\omega'^2_n}{\omega^2_n} = 1 - \frac{\delta_1\delta_2^{-1}sinh^2\left(\frac{\pi i\delta_2}{l}\right) - \delta_1\delta_2^{-1}sin^2\left(\frac{\pi i\delta_1}{l}\right)}{\pi i sinh\left(\frac{2\pi id}{l}\right)} \quad (2)$$

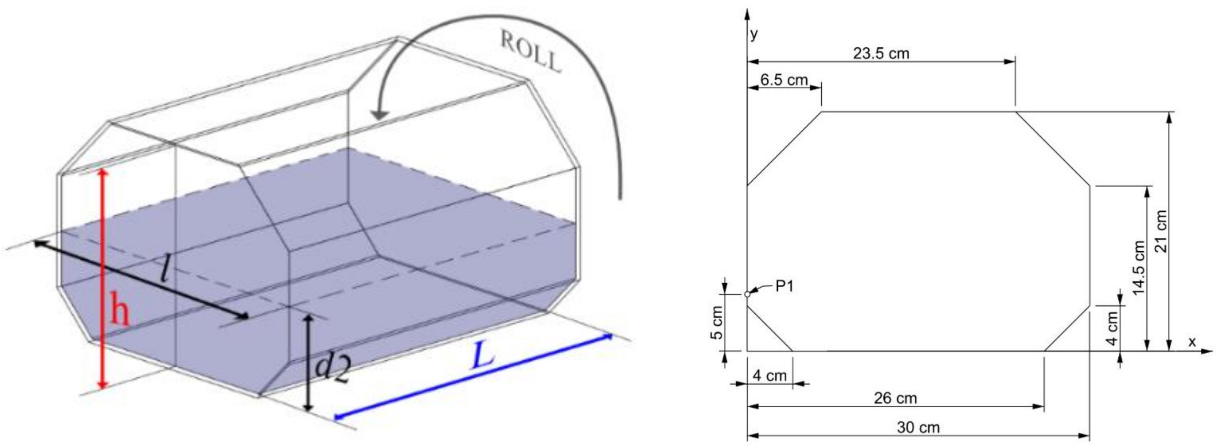


Fig. 1. Sketch of numerical domain and position of pressure sensor

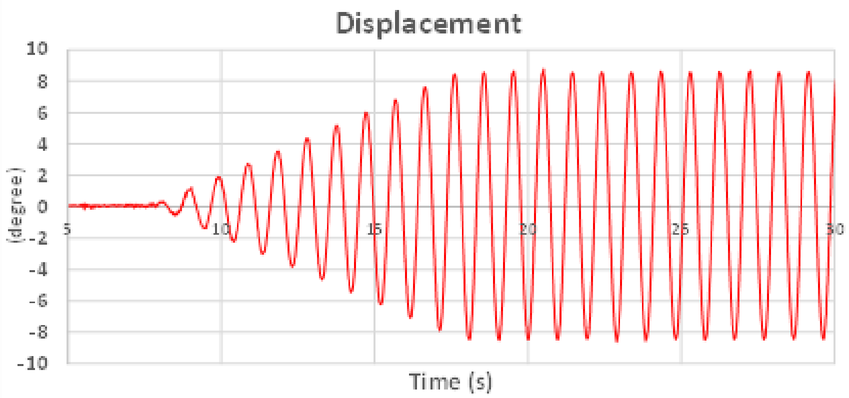


Fig. 2. The time history of tank displacement in rolling motion

2.2 Smoothed Particle Hydrodynamics (SPH)

Smoothed particle hydrodynamics (SPH) was first used by Monaghan [9] and Lucy [31] in the field of astrophysics. Later, Monaghan developed it for free surface flow [9]. SPH is a meshless, Lagrangian approach that estimate the physical values and derivatives of a continuous field employing discrete evaluation points. The mass, velocity, and position are calculated with weighting function or kernel. To reduce the range of contribution from close particles, the quantities are calculated as a weighted sum from those particles within the smoothing length (*h*). The SPH approach's main features, which are based on integral interpolants, are described in detail in Ref. [32].

The smoothing length is used to smooth any particle's contribution to the kernel function, where W_{ab} is the kernel function and r_{ab} is the distance between particles *a* and *b*. (see Figure 3). In Eq. (3), where W_{ab} and $\boldsymbol{r}_{ab}$ are the kernel function and vector position, respectively, the integral approximation field function *A(r)* in domain shown in Eq. (3). Eq. (4) illustrates the particle approximation with a sum of the nearby particles with respect to the compact support of particle *a* at spatial point ***r***. In this study, Wendland kernel function was used in all simulations, where α_D is equal to $21/164\pi h^3$ in 3D, *q* is the nondimensional distance between particles *a* and *b* represented as *r/h* in Eq. (5). Eq. (6) is the continuity equation with the delta-SPH term to reduce spurious pressure in SPH. Eq. 7 is the momentum equation in the SPH framework, where **g** is gravity due to acceleration, P_a and P_b are pressures in particles *a* and *b*. Πab is the artificial viscosity term, where $\mu_{ab} = h\boldsymbol{v}_{ab} \cdot \frac{\boldsymbol{r}_{ab}}{(\boldsymbol{r}_{ab}^2+\eta^2)}$, $\eta^2 = 0.01h^2$ $\bar{c}_{ab} = 0.5(c_a + c_b)$ is the mean speed of sound, and α is a coefficient of artificial viscosity that needs to be tuned to acquire proper dissipation.

DualSPHysics is based on weakly compressible SPH (WCSPH), and an equation of state based is used in WCSPH showed on Eq. (8), where c_o, ρ_0, and γ are the speed of sound at the reference density, and polytrophic constant, respectively. Because this equation is rigid, even one small change in density causes pressure to oscillate. This is one of the reasons why there is a pressure oscillation in WCSPH. Figure 4 illustrates vertical and horizontal baffles configurations. In this study, we use ratio of water depth with height of baffles are 0.7, 0.8, and 0.9, respectively. In addition, horizontal baffles height is 0.1, 0.2, 0.3 and 0.4 from free surface in calm condition. The advanced post-processing in SPH illustrates Figure 5 (c), the visualization was carried out in Blender 2.92. It noticeable that visualization of post processing in SPH seems realistic as seen in the experiment (see Figure 5 (d)). Table 1 indicates shows the parameters setup for SPH computation. Wendland kernel was used in all computation, with time step Symplectic algorithm. Artificial viscosity coefficient 0.01 used to get proper diffusion term, and coefficient speed of sound 60 used. Particle distance was 16 mm that led to total particle 1.306.818. The coefficient of smoothing length 12 used with CFL number 0.2. Delta-SPH 0.1 was used to reduce pressure oscillation and a physical time is 28 seconds with total runtime 78401.03 seconds.

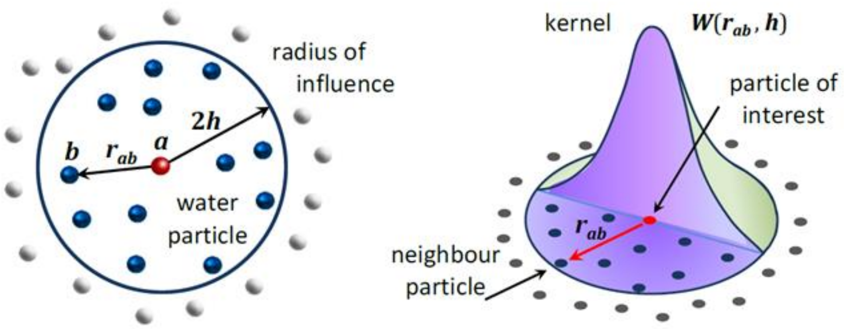


Fig. 3. Radius of the smoothing length and kernel function in SPH

$$A(\boldsymbol{r}) = \int_{\Omega} A(\boldsymbol{r}) W(\boldsymbol{r} - \boldsymbol{r}', h)\, d\boldsymbol{r} \tag{3}$$

$$A(\boldsymbol{r}_a) \approx \sum_b A(\boldsymbol{r}_b) W(\boldsymbol{r}_a - \boldsymbol{r}_b, h) \frac{m_b}{\rho_b} \tag{4}$$

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

$$\frac{d\rho_a}{dt} = \sum_b m_b \boldsymbol{v}_{ab} \cdot \nabla_a W_{ab} + 2\delta_{\Phi} h c_0 \sum_b (\rho_{b-}\rho_a) \frac{\boldsymbol{r}_{ab} \cdot \nabla_a W_{ab}}{\boldsymbol{r}_{ab}^2} \frac{m_b}{\rho_b} \tag{6}$$

$$\frac{d\boldsymbol{v}_a}{dt} = -\sum_b m_b \left(\frac{P_{a+P_b}}{\rho_a \cdot \rho_b} + \Pi_{ab}\right) \nabla_a W_{ab} + \mathbf{g} \tag{7}$$

$$where\ \Pi_{ab} = \begin{cases} \dfrac{-\alpha \overline{c_{ab}} \mu_{ab}}{\overline{\rho_{ab}}} & \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} < 0 \\ 0 & \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} > 0 \end{cases}$$

$$P = \frac{c_0^2 \rho_0}{\gamma} \left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{8}$$

Table 1
Parameter setup of the SPH computation

Parameters	
Kernel function	Wendland
Time step algorithm	Symplectic
Artificial viscosity coefficient (α)	0.01
Coefound	60
Particle spacing (mm)	16
Coefh	1.2
CFL	0.2
Delta-SPH (δϕ)	0.1
Simulation time (s)	28

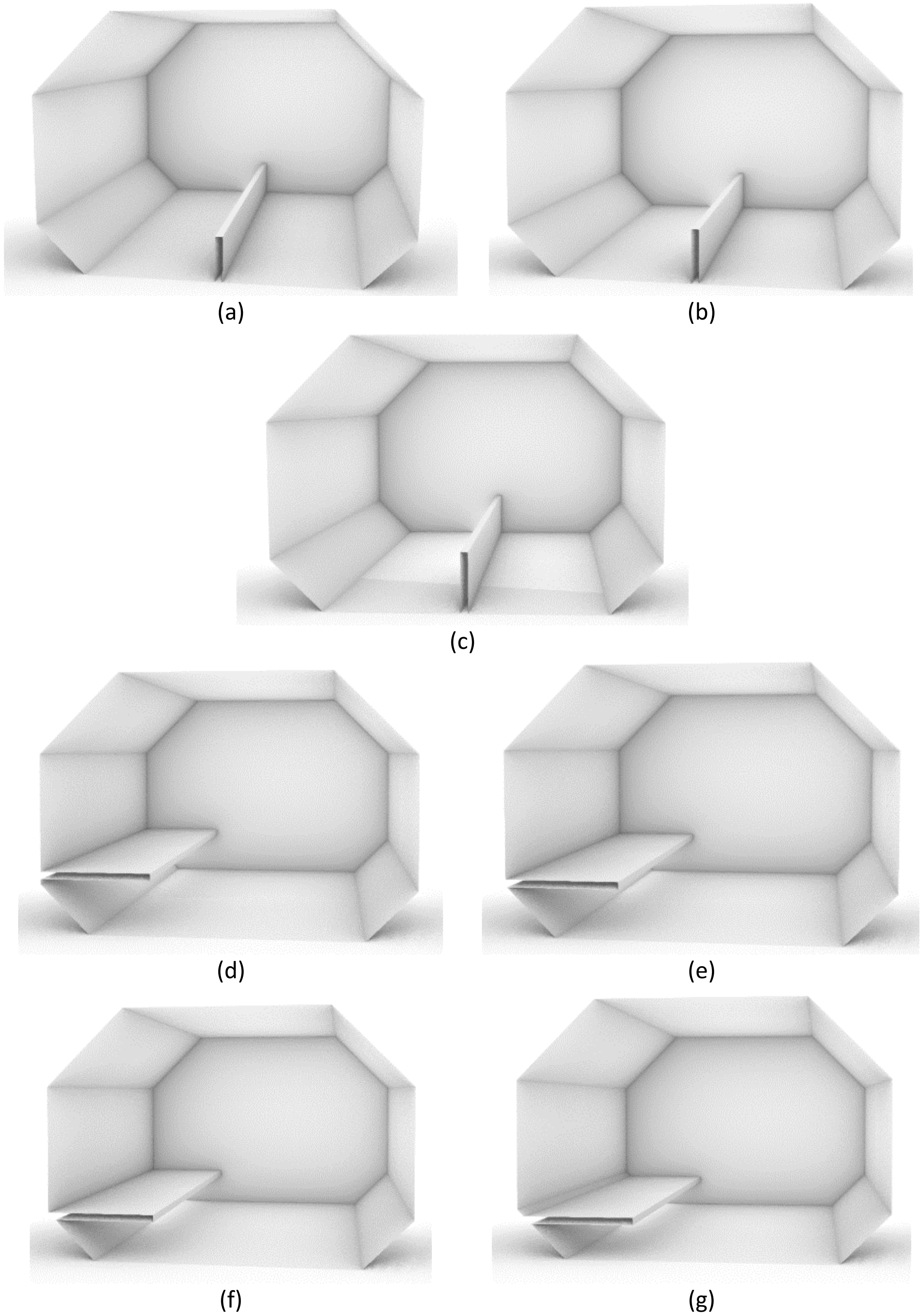


Fig. 4. Variations in Tank Shapes Vertikal baffle (a) 0.7, (b) 0.8, (c) 0.9; and Horizontal baffle (d) 0.1, (e) 0.2, (f) 0.3, (g) 0.4

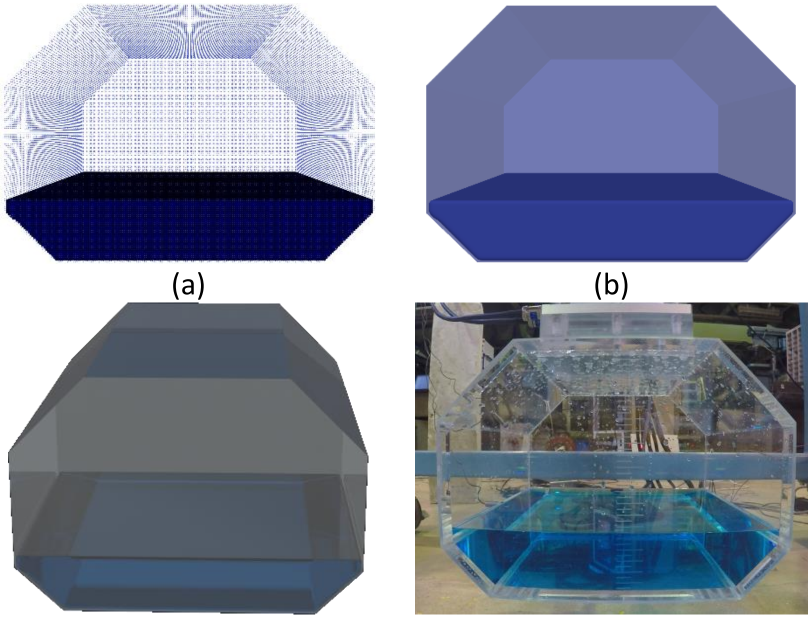


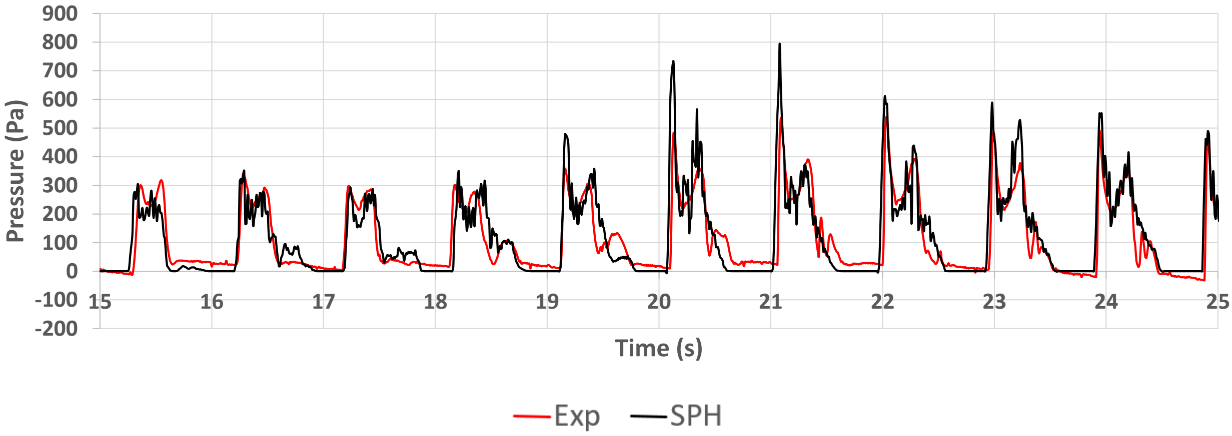
Fig. 5. (a) Visualizations of the particle (b) iso-surface (c) surface texture and (d) experiment

3. Results
3.1 Dynamic Pressure

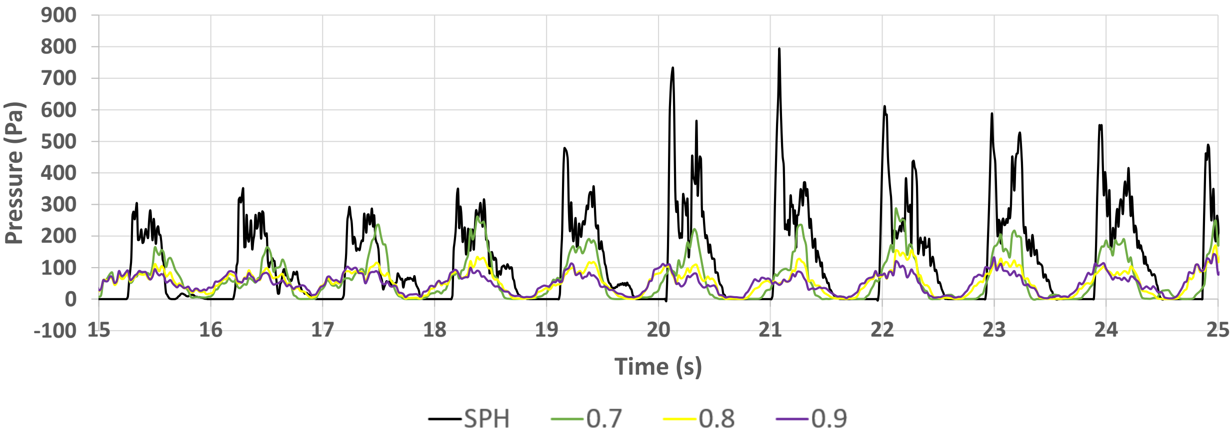
This section discusses the dynamic pressure of sloshing in the prismatic tank from SPH result. Figure 6 illustrates a dynamic pressure without a baffle and with a vertical and horizontal baffle. The red and black are experimental and SPH. Figure 6 (a) shows there is some spurious pressure that peak pressure in 20 and 21 seconds overestimated compare with experiment. This one of classical problems in WCSPH because equation of state is rigid that small change in density could made pressure oscillation. Although in DualSPHysic delta-SPH was used, it only reduced the pressure oscillation not remove the pressure noise. Therefore, the gap between boundary and fluid particles must be considered to contain the typical pressure probe. Because by default DualSPHysics use Dynamic Boundary Condition that When using DBC in SPH simulation, a gap between fluid particles and boundary particles occurs, caused by an artificial force exerted on the boundary particles. It makes the point measurements by the pressure probe rather difficult to set on exact positions on the wall. Figure 6 (b) shows comparison of dynamic pressure of prismatic without and with vertical baffles. It was showed the ratio of 0.9 is the most effective reduced dynamic pressure compare others configuration. Based on previous studies the ratio of baffle height and water depth 0.9 is the effective to reduce dynamic pressure [20, 21]. The reduction is over 80% it can be seen Figure 7 (d) that water becomes calm and there is no impact pressure to wall of tank. It is slightly different from Figure 7 (b) that water still run up to wall though minor, and similar result Figure 7 (c) shows water become calm. Figure 6 (c) illustrates dynamic pressure without and with horizontal baffles, which is in this configuration distance from free surface 0.1 showed the effective ratio height to reduce dynamic pressure. Horizontal baffle was reduced the dynamic pressure by reduction of wave in free surface that impact pressure weakens because the velocity reduced by baffle. The best configuration shows in ratio 0.1, it can be seen in Figure 7 (e) run up of fluid is very minor compare another configuration (see Figure 7 (f)-(g)).

Figure 8 shows the snapshot of free surface deformation using vector velocity in the maximum position. It shows that vertical and horizontal baffles, effectively damped the fluid movement.

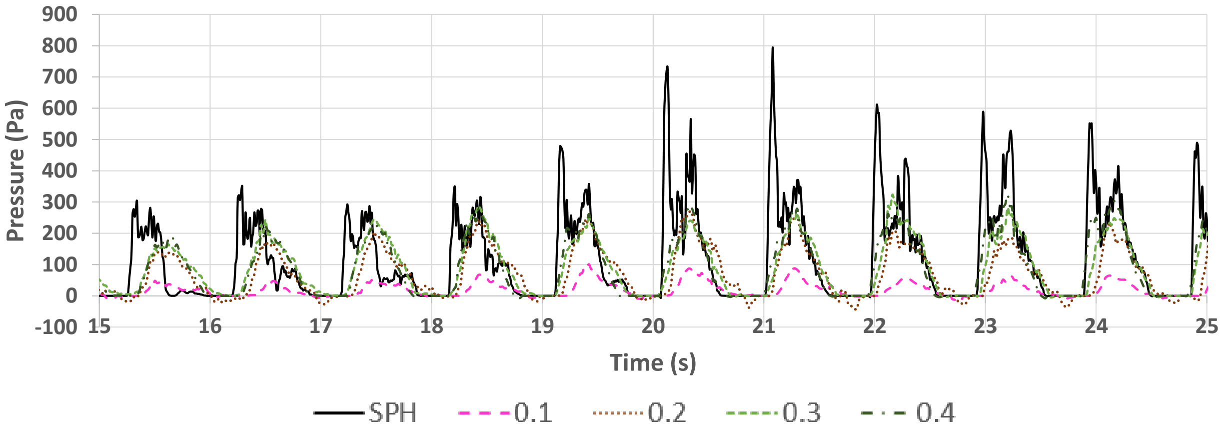
Though sloshing is violent in this situation, the baffle could reduce the wave created by sloshing flow. The fluid looked like in the rest condition, as a result, the dynamic pressure was decreased, as shown in Figure 7.



(a)



(b)



(c)

Fig. 6. Comparison of dynamic pressure for SPH and experiment (a) without baffle, (b) with vertical baffle, and (c) horizontal baffles

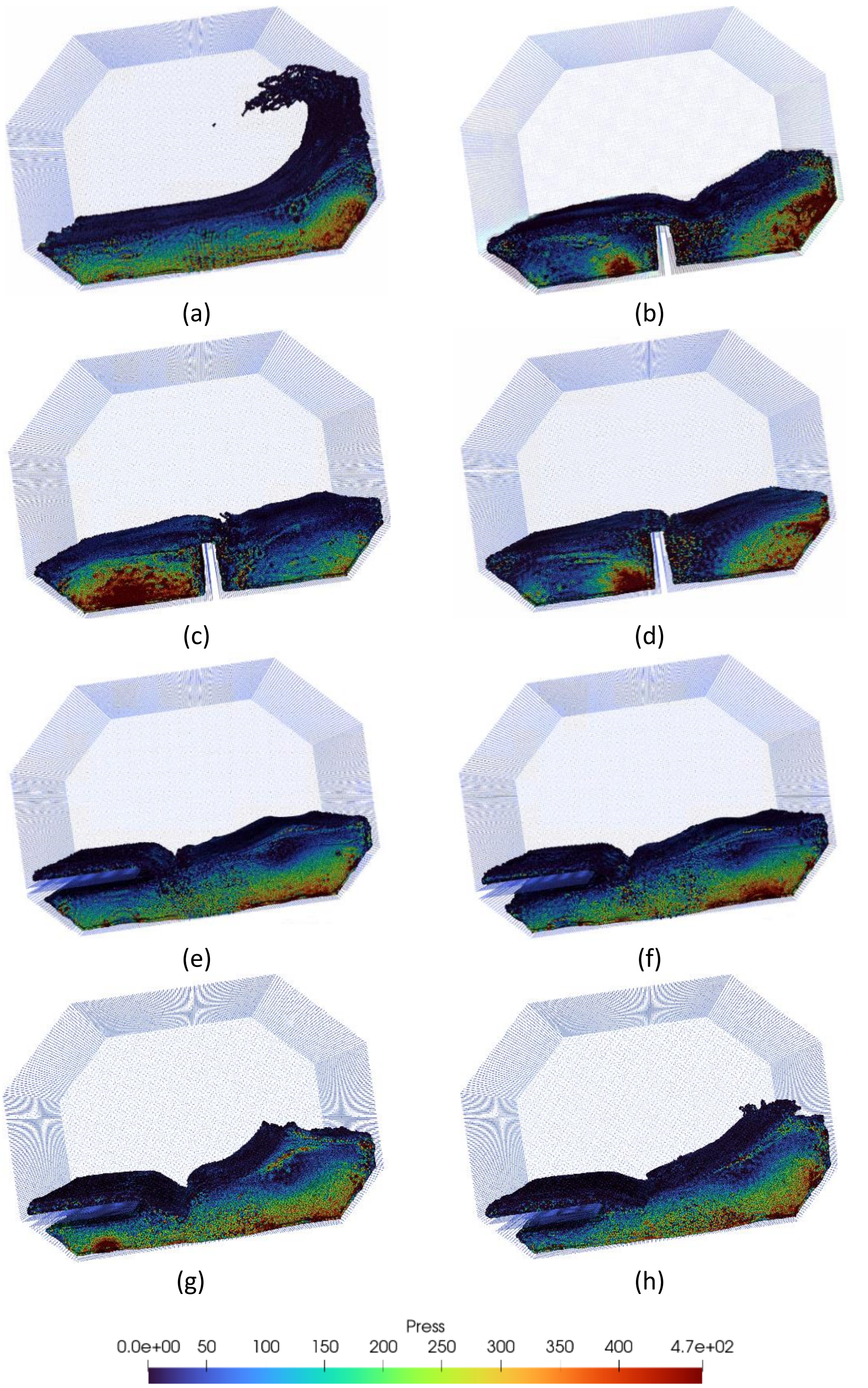


Fig. 7. Pressure contour of dynamic pressure (a) without baffle; vertical baffle (b) 0.7, (c) 0.8, (d) 0.9; and Horizontal baffle (e) 0.1, (f) 0.2, (g) 0.3, (h) 0.4

3.2 Free Surface Deformation

The free surface deformation of sloshing in the prismatic tank was carried out Using Blender 2.92 for improved visualization. Advanced post-processing visualization has become easier to do thanks to VisualSPHysics, fluid has much more attractive texturing than isosurface or particle form. Figure 8 illustrates the vector velocity for sloshing without and with baffles. It can be seen without baffle velocity of fluid faster and wave created after fluid forced to move in opposite wall. The fluid velocities reduces because fluid blocked by vertical baffle and velocities decreased as seen in Figure 8. There is vorticity because fluid pass the baffle and spinning after pass the baffle as results the fluid velocities decreased and fluid becomes calm. It indicates vertical baffle effectively reduce movement of fluid and there is no wave created. Horizontal baffle is reduced velocities as results of fluid pass the baffle in the near free surface and dampened wave.

Figure 9 illustrates free surface deformation both with and without a baffle using VisualSPHysics. The findings suggested that a baffle could lessen sloshing-induced waves. A vertical baffle led the fluid become calm, and similar outcomes are depicted in Figure 8. The fluid is more realistic when generated using VisualSPHysics that mimic real fluid. When compared to mesh-based CFD, the results are one of the merit particle approaches. Particle methods like SPH will have prosperous future in science and entertainment. Further work will need to be carried out for two-phase SPH in 3D model to see effect of the mixture air and water.

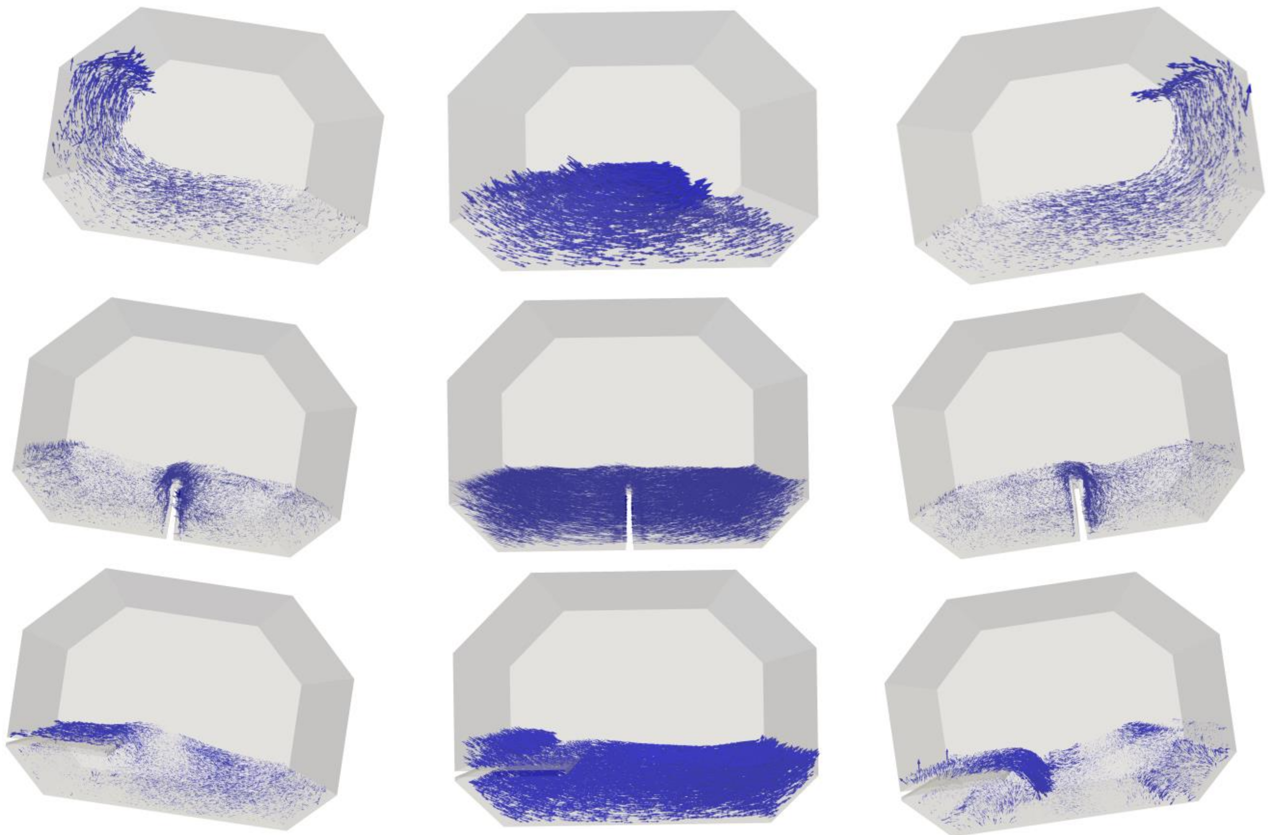
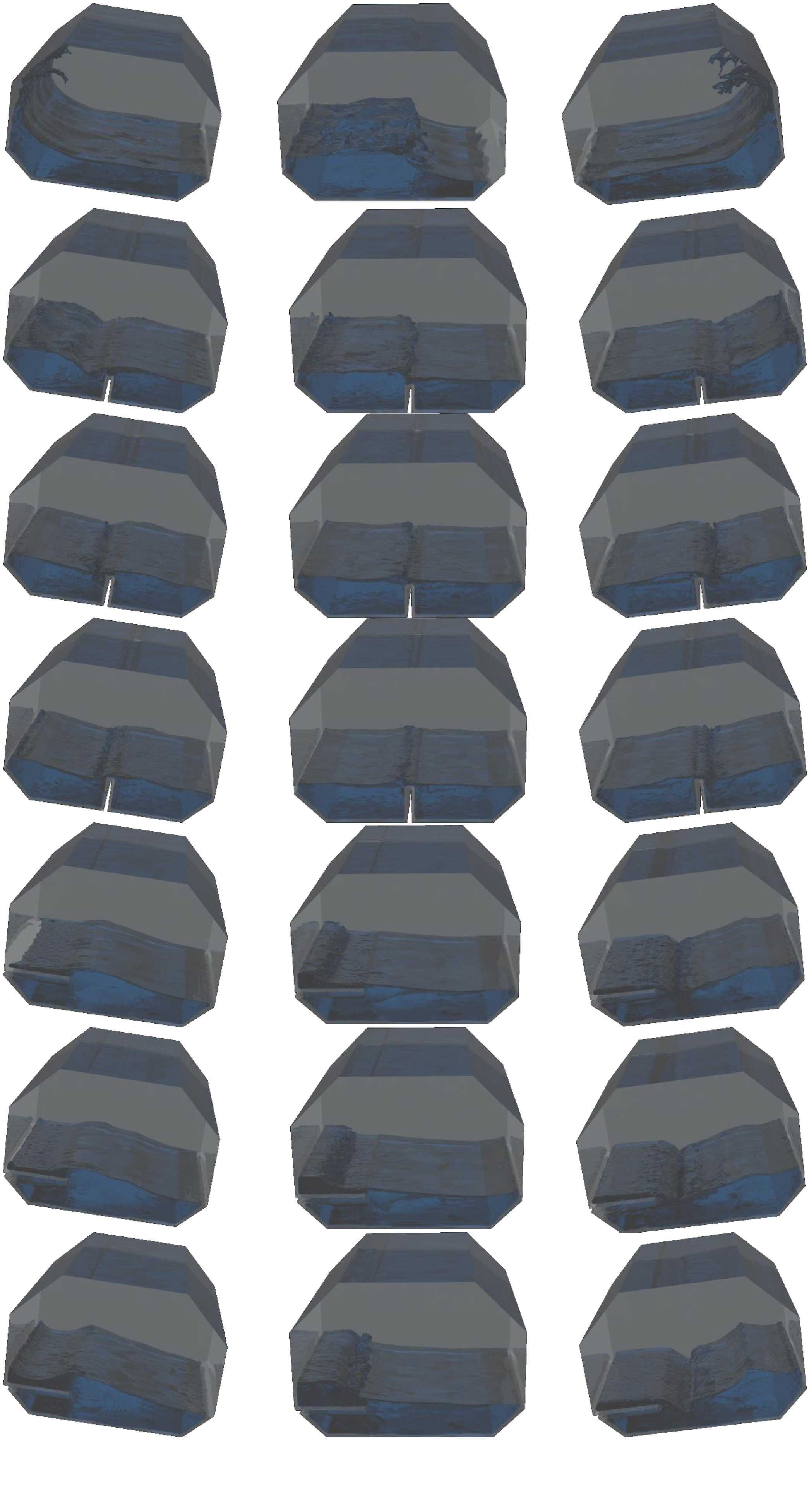


Fig. 8. Comparison of vector velocity inside tank with and without baffles



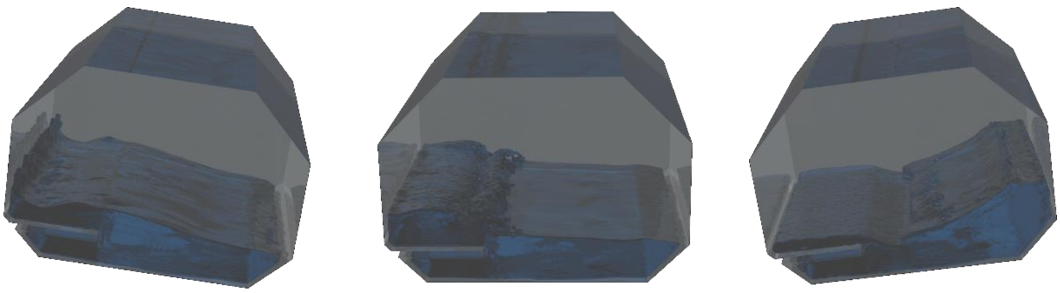


Fig. 9. Comparison of free surface deformation inside tank without and with baffles

3.3 Hydrodynamic Force

The hydrodynamic force of sloshing in the prismatic tank without and with baffle is discussed in this section's findings. The fluid inside the tank was made to move by an oscillation mechanism, resulting in the existence of hydrodynamic force. Figure 10 shows a comparison of the hydrodynamic force with vertical and horizontal baffle; the black, green, yellow and purple lines, is represent SPH, vertical baffle 0.7, 0.8, and 0.9, respectively. The hydrodynamic force is greater without a baffle installed than it installed with baffle. The similar indicates from horizontal baffle, which is horizontal baffle could reduce the hydrodynamic force but not significant as showed in dynamic pressure. It was discovered that a baffle might lower hydrodynamic force by less than 10 % compared without baffle. Thus, the installation of baffles may be an alternative to lessen sloshing in prismatic tanks.

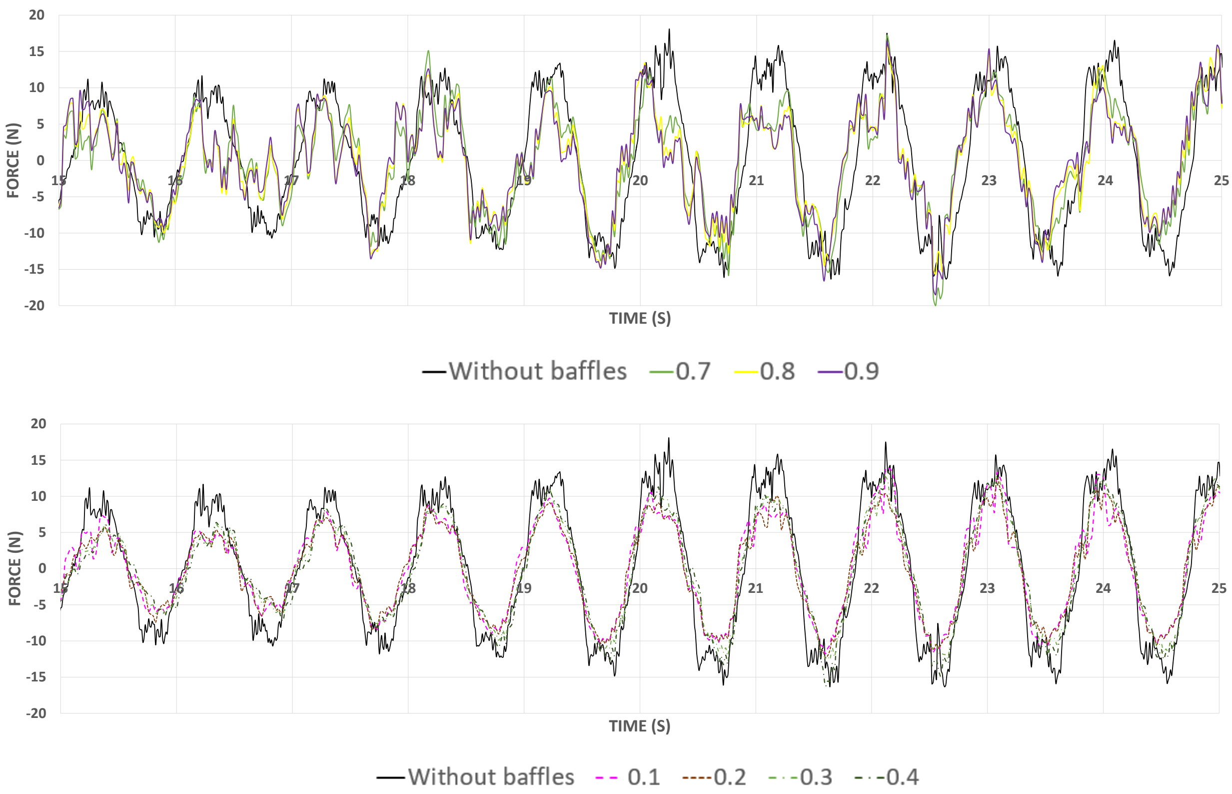


Fig. 10. The hydrodynamic force with vertical baffle (a) and horizontal baffle (b)

4. Conclusions

Numerical simulation of sloshing in prismatic tank was done in meshfree CFD using SPH, it shows particle method as one of the promising methods for violent free surface flow. The findings indicate that baffles both vertical and horizontal baffles, are effective reducing sloshing in a prismatic tank. Additionally, they successfully reduced the dynamic pressure produced on by energetic sloshing. The dynamic pressure was decreased by the vertical and horizontal baffles in accordance with the linear effect on wave height. The effective configuration is 0.9 for vertical baffle and 0.1 is for horizontal baffle. Similar to the dynamic pressure phenomenon, these baffles successfully lowered the hydrodynamic force. In addition, a sophisticated post-processing method employing VisualSPHysics was used to obtain realistic fluid visualization. It was demonstrated that SPH may be applied to both scientific research and other objectives, including entertainment and industrial application. Nonetheless, future research of two-phase SPH for three dimensions of prismatic tank with baffles need to carry out.

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