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Numerical Simulation Low Filling Ratio of Sway Sloshing in the Prismatic Tank Using Smoothed Particle Hydrodynamics

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ABSTRACT

Sloshing is one of challenging problem in the free surface flow, because is dealing with large deformation of fluid. The present paper was carried out of numerical sloshing in the prismatic tank that resemble of LNG membrane type carrier. Pressure sensor was used to validate the dynamic pressure in low filling ratio of tank. Forced oscillation motion in sway with f = 1.08 Hz and amplitude of motion 6.52 mm. A single, and double vertical baffles are used to reduce dynamic pressure and hydrodynamic force. The ratio of baffle heigh with water depth is 0.9. A meshless computational fluid dynamics (CFD) was used to reproduce sloshing in the prismatic tank. Smoothed particle hydrodynamics (SPH) is one of the major meshless CFD. In addition, The advanced visualization was performed using Blender version 2.92. The results showed the vertical baffles effectively reduce the dynamic pressure and hydrodynamic force. Moreover, the advanced visualisation made sloshing simulation more realistic, and attracting compare conventional SPH post-processing.

1. Introduction

Sloshing is one of challenging problem in the free surface flows, because is dealing with large deformation of fluid. Sloshing is one of natural phenomenon in liquid carrier caused resonance of tank caused by external oscillation force. The liquid carrier is mostly dealing with sloshing for instance liquified natural gas /LNG ship. The study of LNG ship with and without bulbous has been carried out to minimize the resistance [1]. The study was conducted for LNG ship membrane type, which the tank is prismatic. The study of sloshing in the prismatic tank has been conducted both experimental and numerical method. Numerical method such as Computational fluid dynamics (CFD) has been wide uses to solve free surface flow not only sloshing but also medical, marine engineering, mechanical engineering [1-6]. Because sloshing is dealing with large deformation of fluid, the particle method is suitable to tackle this problem. One of the major particle methods is smoothed particle hydrodynamics (SPH) that developed for free surface by Monaghan [7]. SPH is a Lagrangian method

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and categorized as meshless CFD because there is no need to generate mesh. Although SPH developed in two decades ago, it was showed SPH is a promising method for free surface flow.

The study of sloshing has been conducted by many reseacher using numerical method supported by development of computer technology. The numerical method itself are consist of mesh-based CFD and meshless CFD. The application of mesh-based CFD for sloshing in the propellant tank using magnetic damping was carried out to mitigate sloshing without baffle [8]. Sloshing simulation in LNG tank was performed both 2D and 3D using VOF [9]. Sway-sloshing in rectangular tank with baffle was performed in mesh based CFD OpenFOAM [10]. Using Arbitarty Lagrangian Euler method sloshing in 3D tank was carried out with experimental validation [11]. A resonant sloshing couples with heave and surge excitations was performed in rectangular tank [12]. Single and double vertical baffles are used to reduce sloshing in the rectangular tank [13]. 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.,* [14]. The study of T-shape baffles was conducted in laminar and turbulence finite volume method by Ünal *et al.,* [15]. The study reveals numerical method is one of major solution in sloshing phenomenon.

The meshless CFD that's well known as particle method has been used for sloshing in tank. The study of sloshing in rectangular with baffle tank was conduct in shallow water tank [16]. The study of sloshing in 3D tank was performed in different compartment shape with analytical validation [17]. The experimental validation of sloshing in the prismatic tank was conducted single- and two-phase flow with weakly compressible SPH (WCSPH) [18, 19]. Therefore, a low pass filter was applied to reduce pressure noise [20]. To mitigate sloshing in the tank elastic baffles are used with coupling Smoothed Finite Element method [21]. Coupled SPH and SPIM was performed to study sloshing with elastic baffles and clamped plate [22]. Futhermore, coupled SPH with the smoothed finite element method (SFEM) was carried out by Zhang *et al.,* [23]. The study of sloshing with vertical and T-shape baffle was performed in prismatic tank Trimulyono *et al.,* [24]. The study shows SPH one of particle method that has a good accuracy for capture large-deformation.

The present study is carried out numerical study of sloshing in the prismatic tank with sway motion. The sloshing experiment was based on Trimulyono *et al.,* [18], which, the filling ratio of tank is 25 %. One pressure sensor located close to free surface was used to validate with experiment. In addition, comparison of free surface deformation and hydrodynamic force with and without baffle was conducted. The baffles are single and double vertical baffle, which ratio of baffle with water depth is 0.9. An open-source SPH solver so-called DualSPHysic version 5.0 was used in this study [25]. In addition, the advanced post-processing of SPH is carried out using Blender 2.92 [26]. Many studies have been carried out for sloshing, but there are a few studies carried out with advanced visualisation, such as Blender. This technique will expand the use of SPH for scientific aims and other purposes such as entertainment and industrial. Using VisualSPHysics, the post-processing became more attractive, and a realistic simulation could be produced. The study revealed the vertical baffles are effectively reduced the dynamic pressure and hydrodynamic force.

2. Methodology

2.1 Experimental Setup

The experimental condition of sloshing was based on Trimulyono *et al.,* [18] work, which a prismatic tank was used to resemble a membrane LNG carrier compartment. Forced oscillation machine was used to move the tank in the four degree of freedom (4 DoF). Three pressure sensor were used to measure dynamic pressure. Location of pressure sensor in the mid of tank and only pressure sensor located in bottom was used to validate the SPH results. Figure 1 depicts the situation of sloshing experiment for filling ratio of 25 %. The experimental itself was conducted in three filling ratio, in this paper only filling ratio of 25 % was used to reproduce sloshing in the low filling ratio. In the low filling ratio sloshing, it became more dangerous compare other filling ratio situation caused the movement of fluid more violent, in addition fluid has characteristic to move with the tank movement that can endanger ship. An excessive motion could be existed due to of sloshing in ship compartment. This is the reason the mitigation of sloshing in the low filling ratio is essentials for liquid carrier for instance LNG carrier. Figure 2 depicts the sketch of prismatic tank for SPH computation. In this paper, only sway motion was used to reproduce sloshing in the low filling ratio. The pressure sensor was fixed during sloshing in the experiment, the similar condition was used in the SPH simulation. Figure 3 shows the tank movement of sway sloshing in the experiment, the same movement was used in the SPH computation. The external frequency excitation is 1.08 Hz, with an amplitude of motion is 6.52 mm. This frequency is close to the natural frequency of a prismatic tank, 1.10 Hz for a filling ratio of 25%. Eq. (1) and Eq. (2) were used to calculate the natural frequency of the prismatic tank [27]. Where ω_n is the natural frequency of the i-mode for a rectangular tank, d represents the water height, and l represents the length of the free surface in the direction of tank movement. For a prismatic tank with a chamfered bottom, δ_1 and δ_2 are the horizontal and vertical dimensions of the chamfer, respectively. For the detailed information regarding sloshing experiment please see the reference by Trimulyono *et al.,* [18].

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

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

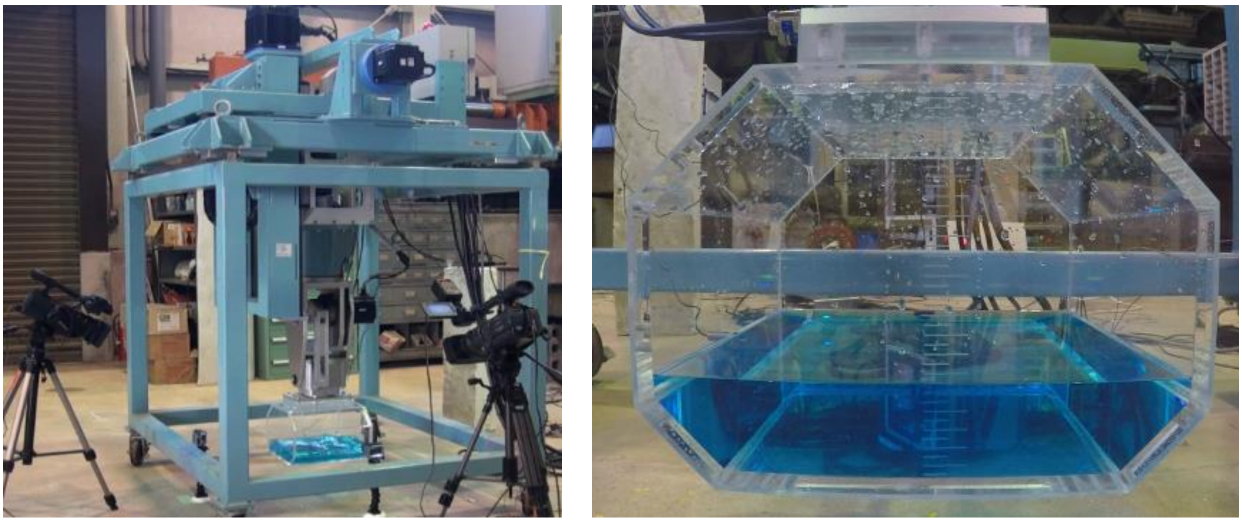

Fig. 1. Sloshing experiment conditions with forced oscillation machine [13]

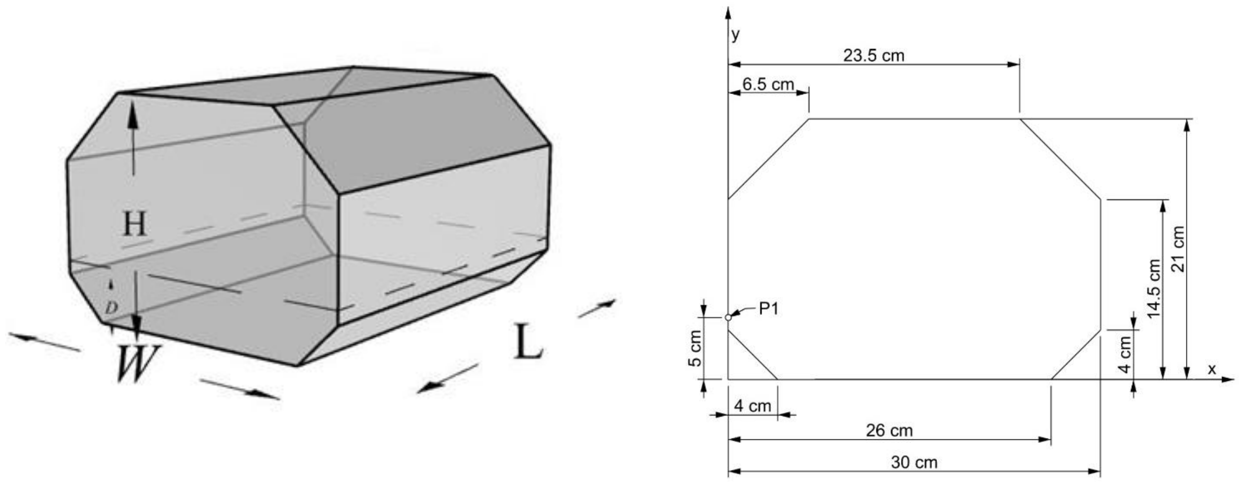

Fig. 2. Sketch of numerical domain and position of pressure sensor

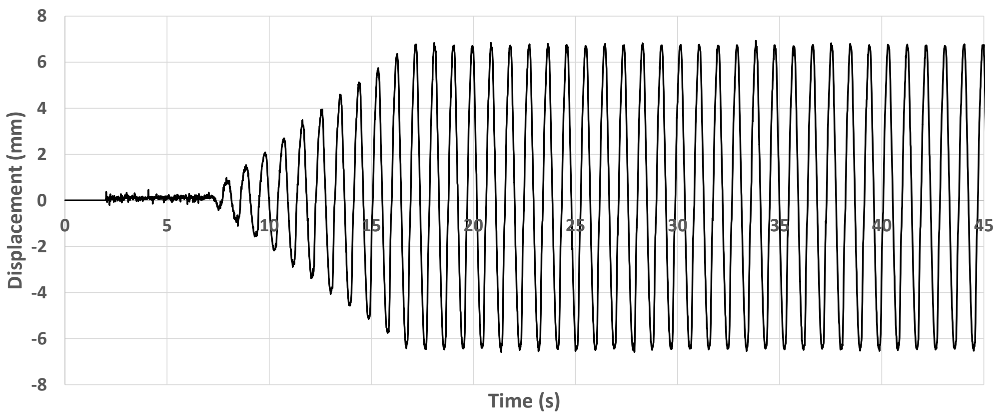

Fig. 3. The time history of tank displacement in sway motion

2.2 Smoothed Particle Hydrodynamics (SPH)

Gingold and Monaghan [28] and Lucy [29] pioneered the application of smoothed particle hydrodynamics (SPH) in the astrophysical field. It was later on developed by Monaghan [7] for free surface flow. SPH is a meshless and Lagrangian method that uses discrete evaluation points to approximate the physical values and derivatives of a continuous field. Smoothed particles are identifiable by their mass, velocity, and position. The quantities are computed as a weighted sum from nearby particles within the smoothing length to decrease the range of contribution from neighboring particles (h). The key aspects of the SPH approach, which is based on integral interpolants, are detailed in a study by Liu and Liu [30].

The smoothing length is used to weigh the contribution of particle in the kernel function, where $\boldsymbol{r}_{ab}$ is the distance between particles a and b and W_{ab} is the kernel function (see Figure 4). The integral approximated field function $A(r)$ in domain shows in Eq. (3), where W and $\boldsymbol{r}$ are the kernel function and vector position, respectively. The particle approximation shows in Eq. (4), with a summation of the neighboring particles regarding the compact support of particle a at spatial position $\boldsymbol{r}$. The 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 that needs to be tuned to acquire proper dissipation.

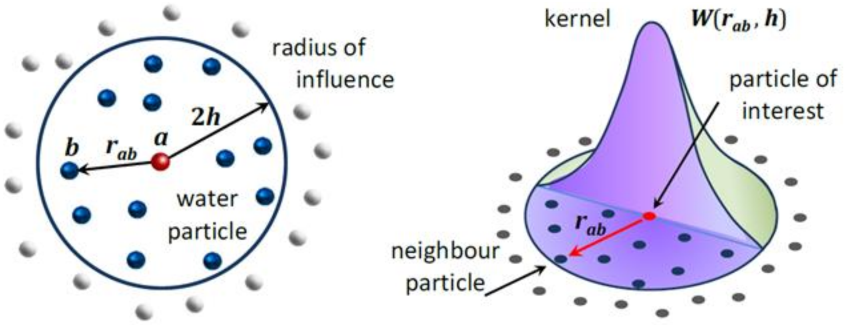

Fig. 4. Radius of the smoothing length and kernel function in SPH [25]

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

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

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

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

$$\frac{d\boldsymbol{v}_a}{dt} = -\sum_b m_b \left(\frac{P_{a+P_b}}{\rho_a \cdot \rho_b} + \Pi_{ab}\right)\nabla_a W_{ab} + \mathbf{g}$$
$$where\ \Pi_{ab} = \begin{cases} \frac{-\alpha \overline{c_{ab}} \mu_{ab}}{\overline{\rho_{ab}}} & \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} < 0 \\ 0 & \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} > 0 \end{cases} \tag{7}$$

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

DualSPHysics is based on WCSPH, and to calculate the pressure in WCSPH, an equation of state based on Eq. (8) was employed, 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 5 shows single, and double vertical baffles configurations. The ratio of baffle height with water depth is 0.9. Moreover, the advanced visualisation of SPH post-processing shows in the Figure 6(c), which the visualisation was carried out in Blender 2.92. It noticeable that visualisation of post processing in SPH looks like real fluid as seen in the experiment (see Figure 6(d)).

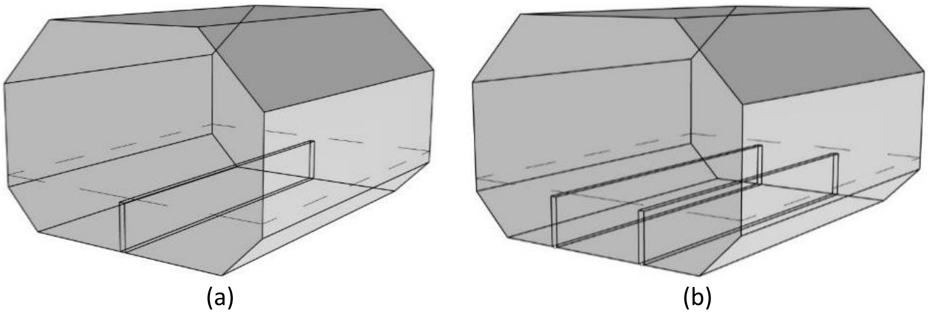

Fig. 5. Sketch of the prismatic tank with a (a) single-vertical baffle, and (b) double-vertical baffle

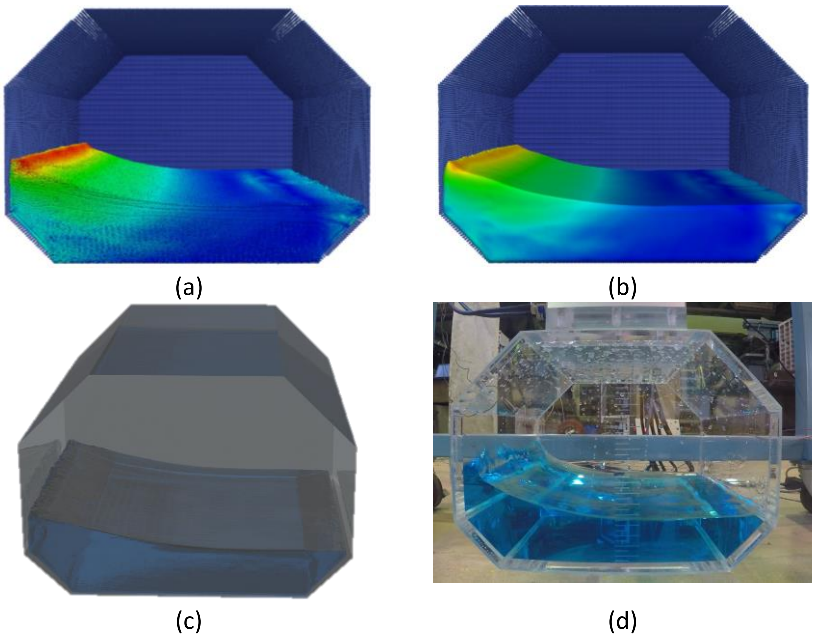

Fig. 6. Visualizations of the (a) particle, (b) iso-surface, (c) surface texture, and (d) experiment

3. Results
3.1 Dynamic Pressure

This section discusses the dynamic pressure of sloshing in the prismatic tank from SPH result. Figure 7 depicts a comparison of dynamic pressure without a baffle and with a vertical baffle. The blue, red, green, and purple lines are an experiment, SPH without baffle, single, and double baffle, respectively. The dynamic pressure without baffle firstly compared to experiment result, it was revealed the dynamic pressure was underestimated especially in time simulation between 15 to 19 second. Later on, the accuracy becomes slightly better. The accuracy slightly decreases compared with sloshing in roll motion, which makes the motion more violent and complicated [19]. The results showed SPH has a prominent accuracy for a violent cases such as sloshing in roll motion. It can be caused by the implementation of delta-SPH that creates instability particles on the free surface. However, in all cases, an additional time simulation of 2 seconds was used to settle down the particle. The accuracy shows deviations in some time, for instance, 15 seconds, caused by Dynamic Boundary Condition (DBC) based on Crespo *et al.,* [31]. 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. Therefore, the gap between boundary and fluid particles must be considered to contain the typical pressure probe. Moreover, the equation of state based on Tait's equations is very stiff. That small change in density creates a significant change in pressure which makes pressure fluctuation in WCSPH. Furthermore, the truncated kernel function decreases accuracy slightly because the pressure sensor is located near the free surface and on the edge of the tank.

The effect of the vertical baffle was visible in Figure 7, that dynamic pressure decreased by over 90 %, similar to a recent study [24]. The vertical baffle dampens the fluid when it passes to the baffle as a result, the wave vanishes. The vertical baffle has effectively reduced the wave in sloshing in the tank as a consequence, the dynamic pressure decreased.

Figure 8 shows the snapshot of free surface deformation in the maximum position in the sloshing simulation. It shows that vertical baffles, both single and double baffles, effectively damped the fluid movement. Although sloshing is moderate in this situation, the vertical 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.

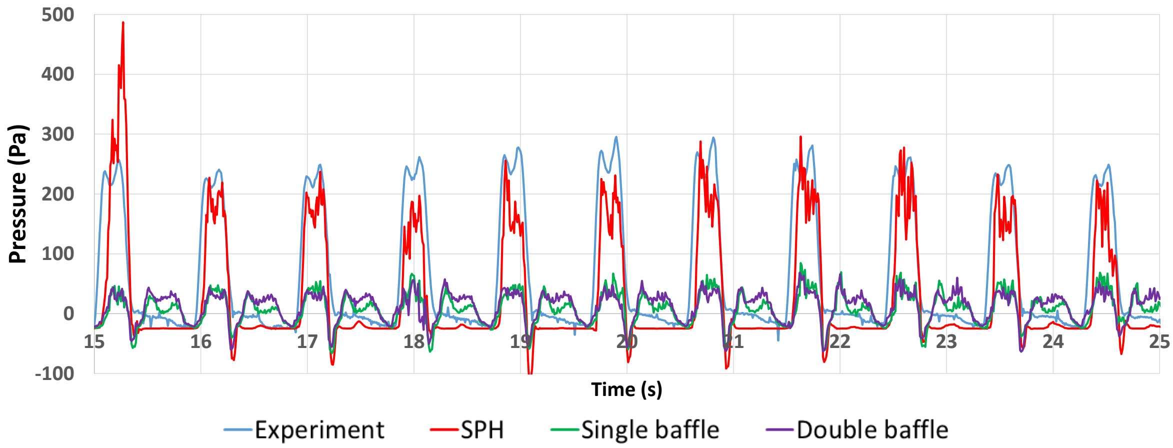

Fig. 7. Comparison of dynamic pressure without and with baffles

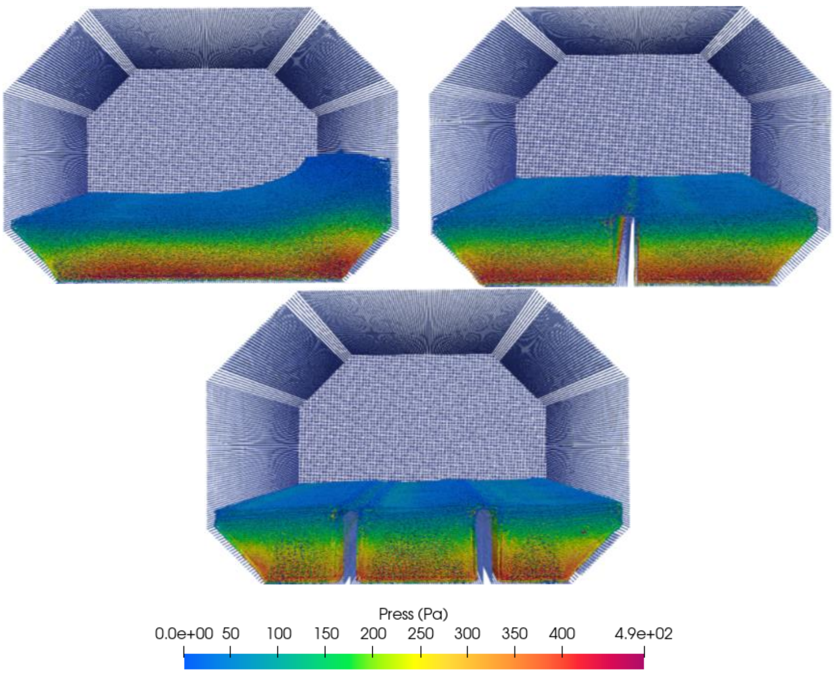

Fig. 8. Snapshot of dynamic pressure for sloshing without and with baffles with t = 15.20 s

3.2 Free Surface Deformation

The free surface deformation of sloshing in the prismatic tank was performed with advanced visualization Blender 2.92. Thanks to VisualSPHysics, advanced visualization of post-processing has become easier to conduct. The texturing of fluid is more attractive compared with iso-surface or particle form. Figure 9 exhibits free surface deformation without and with baffle using VisualSPHysics. The results indicated that baffle could reduce waves caused by sloshing. The fluid became calm caused of a vertical baffle, and similar results showed in Figure 8. Using VisualSPHysics, the fluid is more eye-catching that mimick like real fluid. The result is one of the advanced particle methods compared to mesh-based CFD. The future of particle methods such as SPH will be more promising for science work, industry, and entertainment. Future work on the SPH application for industry cases with advanced visualization needs to be carried out for SPH extension.

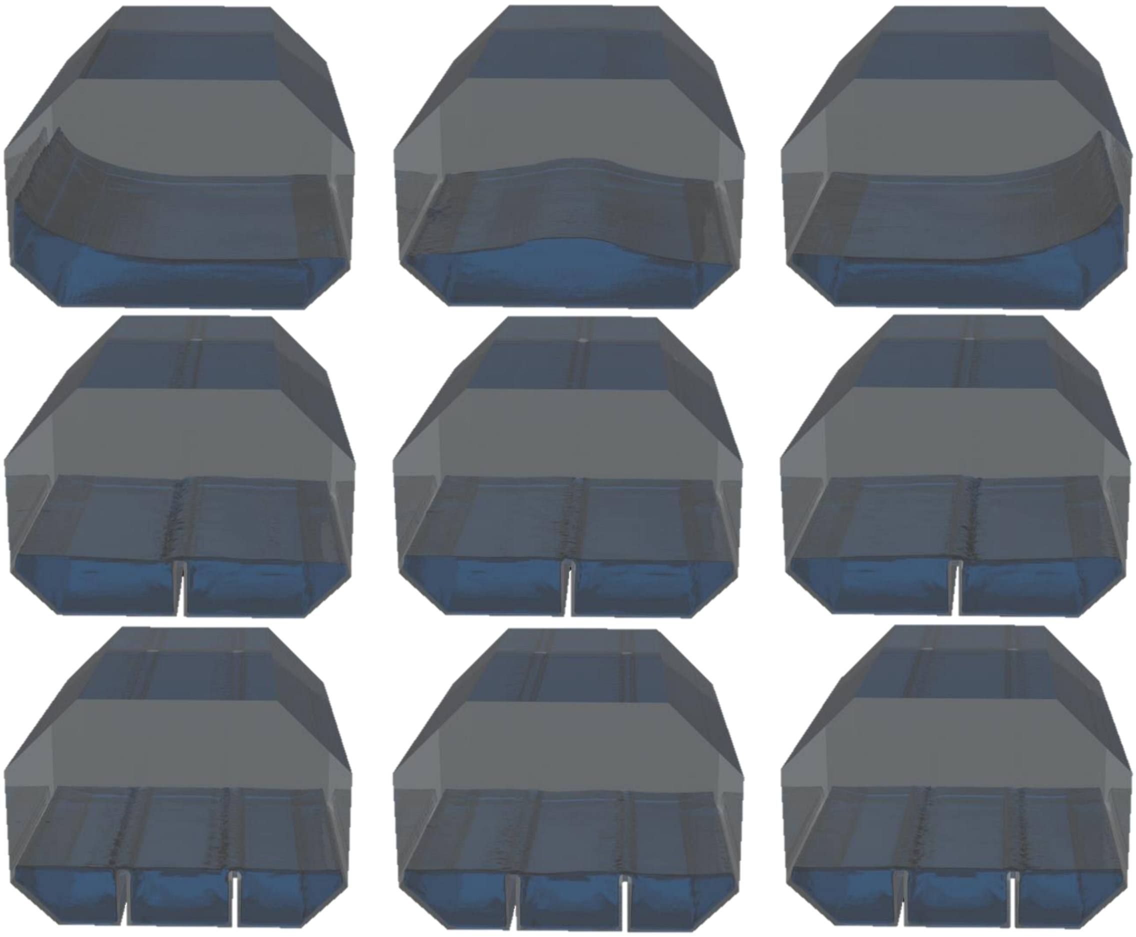

Fig. 9. Comparison of free surface deformation inside tank without and with baffles

3.3 Hydrodynamic Force

This section discusses the results of hydrodynamic force of sloshing in the prismatic tank without and with baffle. Hydrodynamic force exists because the fluid inside the tank was forced to move by an oscillation machine. Figure 10 depicts the comparison of the hydrodynamic force without and with baffle, the red line, green line, and purple line are SPH, single baffle, and double baffle, respectively. The hydrodynamic force without a baffle is higher than that with the baffle installation. The hydrodynamic force in the tank was caused by constantly forced oscillation during the sloshing period. It was revealed that a baffle could reduce hydrodynamic force by over 50% compared to baffle. The movement is translational motion making the difference is higher than rotation motion because the dynamic pressure significantly affects hydrodynamic force. Hence, the use of baffles could be an alternative to reduce sloshing in the prismatic tanks.

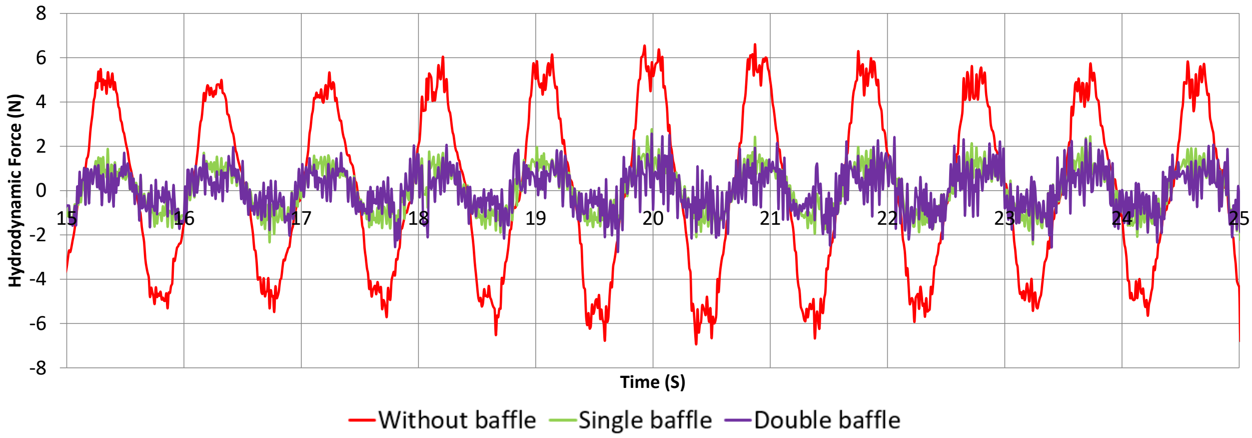

Fig. 10. The hydrodynamic force with and without baffles

4. Conclusions

The sloshing simulation in the prismatic tank was performed using SPH in the low filling ratio. SPH, one of the promising approaches, was used to reproduce it. The findings show that single and double vertical baffles effectively reduce sloshing in a prismatic tank. They also effectively reduced dynamic pressure induced by energetic sloshing. The single and double vertical baffle declined the dynamic pressure, in line with the linear effect in the wave height. These baffles effectively reduced the hydrodynamic force, similar to the dynamic pressure phenomenon. In addition, an advanced post-processing technique using VisualSPHysics was performed to get realistic fluid visualisation. It was shown that SPH could be used for scientific purposes and other purposes such as entertainment and industrial purposes. Nonetheless, more research is needed to evaluate the impact of sloshing on coupled or ship motions in future works.

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