Numerical Investigation of Sloshing in Rectangular Tank with Permeable Baffle

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Received: 28 July 2020; Accepted: 24 August 2020; Published: 1 September 2020

Abstract: Violent sloshing induced by excitation with large amplitudes or resonant frequencies may result in structural damage of the liquid-tank or even the overturning of the liquid cargo transport system. Therefore, impermeable and permeable vertical baffles were investigated numerically to suppress sloshing. The numerical simulations were based on the finite element method and arbitrary Lagrangian–Eulerian (ALE) method. The numerical model was verified by the available experimental data, numerical results and linear theoretical results. Based on the study of the effects of impermeable baffle height, amplitude and frequency of excitation on sloshing, the effects of baffle permeability on sloshing were investigated. Importantly, a critical permeability coefficient that was most effective to suppress sloshing was found. In addition, the maximum flow velocities in the tank with a baffle of small permeability coefficient were smaller than those in the tank with an impermeable baffle. While, the maximum flow velocities under a baffle of large permeability coefficient were larger than those in the tank with an impermeable baffle. Vortices were observed in the whole region of the baffle, tank bottom, tank walls and the free surface in the tank with a permeable baffle.

Keywords: sloshing; vertical baffle; permeable baffle; permeability coefficient

1. Introduction

Sloshing is a concern in several fields, including marine science and engineering [1,2]. Sloshing is an oscillation of the free surface of a liquid in an externally excited. Violent sloshing induced by excitation with large amplitudes or resonant frequencies may result in the structural damage of the liquid-tank or even the overturning of the liquid cargo transport system. Therefore, lots of research has been devoted to study sloshing [3–6] and to search for effective ways to suppress violent sloshing. Kim et al. [7] investigated the measurement errors of sloshing basing on a six-degree of freedom motion simulation platform. Trimulyono et al. [8] performed a parametric analysis of smooth particle hydrodynamics (SPH) parameters in a numerical model of sloshing basing on a graphics processing unit (GPU) acceleration technique. Baffles were generally recognized as an effective way to suppress sloshing. The conventional configuration of baffles such as horizontal and vertical baffles have already been investigated to suppress sloshing [9,10]. It was found that the vertical baffle provided more stable damping compared to other types of baffles in cylindrical tanks. Analytical model and experimental investigations [11] indicated that the hydrodynamic damping provided by vertical baffles or horizontal baffles were mainly determined by the size and location of baffles. Akyildiz [12] reported that sloshing became weaker as the baffle height increased. Armenio and Rocca [13] pointed out that the middle of the tank is the position where the baffle is most effective to suppress sloshing.

Baffles with holes can be found in some road tankers carrying fuel oils or liquefied natural gas (LNG). Compared to the conventional baffles, the advantages of baffles with holes are lightweight, small volume, allowing liquid near tank bottom to pass through and enabling large-scale tank payload...
to be increased without compromising safety. Maleki and Ziyaeeifar [14] investigated the horizontal ring and vertical blade baffles, showing that the ring baffles were more effective to suppress sloshing in the cylindrical tanks. Xue and Lin [15] and Xue et al. [16,17] developed a three-dimensional numerical wave tank model to study sloshing dynamics and related problems. In their model, a coupled virtual boundary force–volume of fluid (VBF–VOF) method was proposed to simulate the interaction between free surface wave and the perforated baffle. Xue et al. [18] experimentally studied vertical baffles of different configuration, which was valuable in the design of cargo ship carrying liquid-tank. Faltinsen and Timokha [19] focused on the vertical slat-type screen fixed in a rectangular tank. Basing on the linear sloshing theory and domain decomposition method, they developed an accurate analytical approximation of the natural sloshing modes in a rectangular tank with a slat-type. Faltinsen et al. [20] found that the slat-screens with high solidity ratios played an important role in suppressing sloshing and there was an optimal solidity ratio that was most effective to suppress sloshing. Faltinsen et al. [21] also noted that screens change secondary resonances in the hydrodynamic system. Yu et al. [22,23] experimentally studied the vertical screens to suppress sloshing in a tank under horizontal excitation with a wide frequency range. Suzuki and Kaneko and [24] developed a theoretical model to investigate the effect of punching plates to suppress the sloshing in a horizontal cylinder. Jin et al. [25] analytically study the effect of a horizontal perforated plate on sloshing motion in a rectangular tank.

In recent years, porous material has been introduced as an antiexplosion product in storage tanks to improve tank stability. Porous material has been early investigated in submerged breakwater to reduce the wave height [26]. Abbaspourl and Hassanabad [27] simulated sloshing in a tank filled with porous material and found that porous media was very effective in generating rapid damping to suppress sloshing. He et al. [28] simulated and analyzed the effect of the porosity girder on sloshing by comparing the time histories of free surface elevations. One of the fundamental characteristics of porous materials is that the porous domains are filled with both fluids and solids. The characteristic of porous materials can be quantitatively described by the permeability. However, there has been little report about the sloshing suppression by permeable baffles.

The primary objective of this work is to investigate effects of permeable baffle on sloshing in a rectangular tank. Particularly, numerical simulations were conducted based on the finite element method and arbitrary Lagrangian–Eulerian (ALE) method by automatic dynamic incremental nonlinear analysis (ADINA) solver. Zhu et al. [29] presented the results of modal analysis of the liquid tank using general MSC Nastran software and concluded that it was feasible to utilize commercial software to analyze fluid-structure-interaction (FSI) problems. Wang et al. [30] used the potential flow model in ADINA to simulate sloshing in a rigid cylindrical tank with multiple rigid annual baffles. Eswaran et al. [31] used the Navier–Stokes equation in ADINA to investigate the effects of baffle shapes and baffle arrangements on sloshing. The rest of this paper is organized as follows. Section 2 describes the mathematics model of sloshing. Section 3 verifies the accuracy of numerical results by the available theoretical, numerical and experimental results. Section 4 investigates the effects of baffle height, amplitude and frequency of excitation, and baffle permeability coefficient on sloshing. Section 5 is a brief summary and conclusion of the study.

2. Mathematics Model of Sloshing

2.1. Governing Equations of Fluid Flows

Fluid is assumed to be homogenous, isotropic, viscous and incompressible Newtonian fluid. The governing equations for fluid flow consist primarily of the Navier–Stokes equations, including conservation of mass and momentums. An arbitrary Lagrangian–Eulerian (ALE) description for incompressible viscous flows developed by Hughes et al. [32] is chosen to solve free surface flows and
moving boundaries between fluids and solids. In the ALE description, the material derivative with respect to the reference coordinate can be described as Equation (1).

$$\frac{\partial H(x_i, t)}{\partial t} = \frac{\partial h(x_i, t)}{\partial t} + w_i \frac{\partial h(x_i, t)}{\partial x_i},$$  (1)

where $X_i$ is the Lagrangian coordinate, $x_i$ the Eulerian coordinate, $w_i$ is the moving coordinate velocity and $f$ is a physical variable. Thus the only difference between the ALE formulation and the Eulerian formulation to describe Navier–Stokes equations is that the convective velocity in Eulerian formulation is replaced by the relative velocity in ALE formulation. Under the assumption that the fluid is the laminar flow with constant viscosity, the flow governing equations of the fluid with respect to an ALE system can be expressed as follows [33]. Based on the assumption of laminar flow, the smaller vortices are ignored. The governing equations for fluid flow are solved by direct numerical simulation (DNS). So, the nonlinear (quadratic) damping law caused by the flow separation at the baffle edge can be considered in this model.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left( \rho (u - w) \right) = 0, \quad (2)$$

$$\rho \left( \frac{\partial u}{\partial t} + (u - w) \cdot \nabla u \right) = \nabla \cdot (-p I + \mu (\nabla u + (\nabla u)^T)) + f, \quad (3)$$

where $u$, $\rho$, $p$, $\mu$, $f$, $I$, $w$ and $u-w$ are fluid velocity, fluid density, pressure, dynamic viscosity, the volume force affecting the fluid, the unit diagonal matrix, the moving coordinate velocity (structure velocity) and the relative velocity respectively. The porous model is adopted in this study to simulate the permeability of baffles. In porous media, the material is viewed as a continuum in which the total bulk volume contains a fully fluid solid skeleton. The continuity equation is also valid for the fluid in the porous model. The difference is that the averaged velocity was used to determine the flow properties in porous media. During the averaging procedure, permeability is introduced to quantitatively describe the porosity of the baffle with multiple small holes. The momentum conservation of fluid flowing through porous media can be expressed as Darcy’s law [33] (Equations (4) and (5)). Under the consideration of the moving of the structure in porous media, the velocity in Darcy’s equation becomes the relative velocity.

$$\mu \kappa^{-1} \cdot \nu = -\nabla p + f, \quad (4)$$

$$\kappa = \kappa_{ij} E_i E_j \text{ and } \nu = \varphi \psi = \frac{k}{\mu} \frac{\partial p}{\partial x}, \quad (5)$$

where $\kappa$, $\kappa_{ij}$, $E_i$, $E_j$, $\nu$ and $\varphi$ and $k$ are permeability tensor, permeability coefficient of porous medium, averaged velocity in the porous medium (which should be subtracted from the speed of the moving mesh), Cartesian components, velocity in the porous medium, porosity and heat transfer coefficient respectively. Since the porous medium is shared by both fluid and solid, the material properties are evaluated by

$$m = m_s + \varphi (m_f - m_s) \quad (6)$$

where $\varphi$ is the porosity of the medium, and $m$ represents any property of the fluid–solid mixture, such as $\kappa$. In a pure solid region, the fluid velocity is the same as the solid velocity.

### 2.2. Boundary Conditions

The interfaces between fluid and structure and free surface boundary conditions have to be considered for the accurate solution of fluid flow problems. The boundary conditions of interfaces between the fluid and the structure are no-slip conditions in the laminar model [33] (Equation (7)). The fluid free to move on the top boundary satisfies the stress continuity condition [33] (Equation (8)). The stress in the surrounding environment is neglected.

$$n \cdot u = n \cdot w, \quad (7)$$
where $p_0$ is the surrounding (constant) pressure. In this model, $p_0 = 0$ is adopted.

3. Model Verification and Validation

The present model embedded in ADINA was applied to investigate liquid sloshing. The sketch of the two-dimensional rectangular tank is shown in Figure 1, where symbol $y$ denotes the distance between the wall and the wave gauge, $L$ is the tank length, $h$ is the liquid depth and $H$ is the height of the baffle. The partially filled tank was driven by a harmonic surge excitation following the sinusoidal function: $x = -A \sin (\omega t)$, where $A$ is the excitation amplitude and $\omega$ is the excitation frequency.

![Figure 1. A rectangular tank with a vertical baffle.](image)

3.1. Linear Sloshing in a Clean Rectangular Tank

The results of two linear sloshing cases obtained by the present numerical model were compared with the linear analytical solutions [34] and numerical benchmark from Liu and Lin [35]. The analytical solutions of the free surface elevation ($\eta$) based on potential flow theory are developed by Faltinsen [34] (Equations (9)–(11)).

$$\eta = \frac{1}{8} \sum_{n=0}^{\infty} \sin k_n x \cosh k_n h (A_n \omega_n \sin \omega_n t - C_n \omega \sin \omega t) - \frac{1}{8} A \omega x \sin \omega t, \tag{9}$$

$$C_n = \frac{\omega D_n}{\omega_n^2 - \omega^2}, \quad A_n = -C_n - \frac{D_n}{\omega}, \quad D_n = \frac{4\omega A (-1)^n}{L \cosh (k_n h)} \frac{1}{k_n^2}, \quad k_n = \frac{n \pi}{L}, \tag{10}$$

$$\omega_n = \sqrt{\frac{g k_n \tanh k_n h}{\omega}}, \tag{11}$$

where $\eta$ is the elevation of the free surface, $\omega_n$ is the natural frequency of sloshing in a clean tank and $n$ is the sloshing mode.

The values of the parameters were $L = 1$ m, $h = 0.5$ m, $\mu = 0.001$ Pa·s and $\rho = 1000$ kg/m$^3$, respectively. The lowest natural frequency of sloshing in the clean tank was 5.316 rad/s. In case 1 (Figure 2), $\omega = 0.5 \omega_0$ and $A = 0.01$ m. In case 2 (Figure 3), $\omega = 0.9958 \omega_0$ and $A = 0.002$ m. The mesh used in the numerical simulation were $\Delta x = 0.02$ m and $\Delta z = 0.01$ m. The constant time step was $\Delta t = 0.005$ s. As shown in Figures 2 and 3, good agreements were obtained between the present numerical results and the analytical solution at the early stage of the wave evolution. As time went on, the results of the present model became smaller than the analytical solutions.
Two cases were conducted to test the performance of the present model in solving a nonlinear sloshing wave. In case 3, as shown in Figure 4, the tank parameters were \( L = 0.57 \) m and \( h = 0.3 \) m. The lowest natural frequency of sloshing was \( 7.085 \text{ rad/s} \). The excitation frequency was \( \omega = \omega_0 \) and the excitation amplitude was \( A = 0.005 \) m. In case 4 (Figure 5), \( L = 1 \) m, \( h = 0.06 \) m, \( \omega = 0.874\omega_0 \) and \( A = 0.03 \) m. The fluid domain was discretized by uniform grids with \( \Delta x = \Delta z = 0.01 \) m. The constant time step was \( \Delta t = 0.005 \) s.

Figure 4 shows that the present numerical results are in better agreement with the experiment data than the analytical solution. Obvious resonant phenomenon can be observed in Figure 4, as the excitation frequency is close to the natural frequency of sloshing. The analytical solution, showing a symmetric wave pattern, fails to predict the resonant sloshing where the wave crests are much larger than the troughs. The results indicate that the present numerical model is more accurate in predicting the nonlinear sloshing motion than the theoretical solution. The present numerical results also agreed well with the experiment data of strong non-linear sloshing in shallow depth [36] as shown in Figure 5. As shown in Figure 5, the results imply energy transfer between modes,
which demonstrates the strong nonlinearity of the free-surface sloshing problem. The amplifications of the higher harmonics as well as the corresponding natural modes suggest the possible presence of the secondary resonance phenomenon.

![Figure 4](image-url)  
**Figure 4.** Comparison of the time history of free surface elevation at $y = 0$ between the results of the present simulation, experimental data of Liu and Lin [35] and analytical solution of Faltinsen [34].

![Figure 5](image-url)  
**Figure 5.** Comparison of the time history of free surface elevation at $y = 0.05$ between the results of the present simulation and experimental data of Bouscasse [36].

### 3.3. Sloshing in a Rectangular Tank with a Vertical Baffle

To verify the accuracy of the numerical model in simulating sloshing with baffles, the numerical result was compared with the numerical result from reference [34] (case 5). In case 5, a vertical baffle was fixed in the center of the tank bottom, other parameters were $L = 1 \text{ m}$, $h = 0.5 \text{ m}$, $H = 0.75 \text{ h} = 0.375 \text{ m}$, $\omega = 0.996 \omega_0 = 5.29 \text{ rad/s}$, $A = 0.002 \text{ m}$, $\Delta x = \Delta z = 0.01 \text{ m}$ and $\Delta t = 0.005 \text{ s}$. As shown in Figure 6, our numerical result agrees well with the numerical result from Liu and Lin [34]. It indicates that our numerical model was a robust tool to predict sloshing in a baffled-tank. Comparing Figure 6 with Figure 3, it can be seen that the vertical baffle effectively reduced the free surface elevation.
The present simulations were verified by the experimental data from Wu et al. [37], the asymptotic formula solutions from Faltinsen and Timokha [9,10] and the numerical results from Firoua-Abadi [38]. In these cases, $L = 0.6$ m and $h = 0.3$ m. As can be seen in Figure 7, all solutions were in good agreement when the relative baffle height $H/h$ was less than 0.3. However, as the baffle height increased, the results obtained by the different methods show considerable variation. The results of the asymptotic formula and the BEM (boundary element method) numerical model deviate a little bit from the experimental data. Our numerical results were quite consistent with the experimental data when the height of the baffle was 0.01 m. The tank was driven by a horizontal oscillation $x = -A \sin(\omega t)$.

### 4. Results and Discussion

It was found that vertical baffles were more effective and stable than horizontal baffles to suppress sloshing [9,10]. In our study, the effects of an impermeable and a permeable vertical baffle on sloshing were investigated successively. The tank parameters were $L = 1$ m, $h = 0.5$ m and the thickness of the baffle was 0.01 m. The tank was driven by a horizontal oscillation $x = -A \sin(\omega t)$.

#### 4.1. Effect of Baffle Height on Sloshing

Sloshing becomes weaker as the baffle height increases [12]. However, the total weight, volume and the area subjected to force of the baffle also increase as the baffle height increases. Therefore, a series of numerical experiments varying the baffle height were conducted to find a critical baffle height. The parameters used here were $\omega = \omega_0$, $A = 0.002$ m, $\Delta x = 0.01$ m, $\Delta z = 0.005$ m and $\Delta t = 0.005$ s.

The effect of a vertical impermeable baffle on the natural frequency of sloshing was studied first. The present simulations were verified by the experimental data from Wu et al. [37], the asymptotic formula solutions from Faltinsen and Timokha [2] and the numerical results from Firoua-Abadi [38]. In these cases, $L = 0.6$ m and $h = 0.3$ m. As can be seen in Figure 7, all solutions were in good agreement when the relative baffle height $H/h$ was less than 0.3. However, as the baffle height increased, the results obtained by the different methods show considerable variation. The results of the asymptotic formula and the BEM (boundary element method) numerical model deviate a little bit from the experimental data. Our numerical results were quite consistent with the experimental data when the height of the baffle was high.

In Figure 8, the response of natural frequencies of sloshing in the tank with the dimension of $L = 1$ m and $h = 0.5$ m to baffle height were estimated. Same conclusion in Figure 7, the natural frequency of sloshing became smaller as the baffle height increased. The primary reason for this phenomenon is the ‘compartmentalization’ effect of the baffle. In addition, the natural frequency decreased at the same rate as $H/h$ increased under equal relative water depths $h/L$. The damping ratio ($\xi$) defined as Equation (12) was adopted to further describe the effect of baffle height on the sloshing,

$$
\xi = \ln \left( \frac{\eta_1}{\eta_0} \right) \bigg/ (-\omega_0 \Delta t),
$$

where $\eta_1$ is the initial sloshing amplitude of free sloshing, $\eta_0$ is the new elevation of the free surface after one period of free sloshing and $\omega_0$ is the lowest natural frequency of sloshing in a clean tank.

**Figure 6.** Comparison of the time history of free surface elevation at $y = 0$ between the results of the present simulation and numerical benchmark of Liu and Lin [35].
The sloshing damping ratio in the tank with the dimension of $L = 1$ m and $h = 0.5$ m under a different baffle height are presented in Figure 9.

**Figure 7.** Comparison of the natural frequency of sloshing in a tank ($L = 0.6$ m, $h = 0.3$ m) under different baffle heights between the results of the present simulation, BEM results of Firouz-Abadi [38], experimental data of Wu et al. [37] and asymptotic formula of Faltinsen and Timokha [2].

**Figure 8.** Natural frequency of sloshing in two different sized tanks under different baffle heights.

**Figure 9.** Sloshing damping ratio in the tank ($L = 1$ m, $h = 0.5$ m) under different baffle heights.
The maximum elevations of the free surface at the left tank wall and the tank center under different baffle heights are shown in Figure 10. It can be seen from Figure 10 that the baffle could significantly suppress sloshing. However, the sloshing suppression by the baffle was no longer more effective with the increase of the baffle height, when the baffle height exceeded 80% of the liquid depth. In Figure 11, the time series of free surface elevations in the clean tank exhibited a distinct resonance wave characteristic. The free surface elevations decreased significantly with the increase of the baffle height.

Figure 10. The maximum elevation of free surface at \( y = 0 \) and \( y = 0.5L \) of sloshing in the tank under different baffle heights.

Figure 11. Time series of free surface elevation at \( y = 0 \) of sloshing in the tank under different baffle heights.

Additionally, the velocity distributions are presented to explore the effect of the baffle on sloshing and to discuss the damping mechanisms of the baffle. Figure 12 shows the vertical distribution of the maximum velocity at the tank center, i.e., along the left side of the baffle. In Figure 12, \( Z \) is the ratio
between the distance from the measurement point to the tank bottom and the water depth. The fluid velocity decreased sharply as baffle height increased. The maximum velocity along liquid depth occurred at the top of the baffle, rather than at the free surface, under the baffle heights ranging from 0.2 to 0.8 h. Figure 13 shows the velocity fields of sloshing under different baffle heights at a different time. As the baffle height increased, the near-surface fluid velocity evidently decreased while the near-bulkhead tip fluid velocity obviously increased. Distinct vortex can be observed around the baffle tip, especially in the case $H = 0.8 h$. At the centerline of the tank, the flow became violent and vortexes were always induced to grow because of the reduction of the cross-sectional area and the interaction between the flow and the baffle.

### Figure 12. The vertical distribution of the maximum flow velocity at the tank center under different baffle heights. (a) Horizontal component of velocity; (b) Vertical component of velocity.

### Figure 13. The fluid velocity fields of sloshing in a tank under different baffle heights at different time. (a) $H = 0.0 h$, $t = 5.8 s$; (b) $H = 0.2 h$, $t = 5.8 s$; (c) $H = 0.8 h$, $t = 5.8 s$; (d) $H = 0.0 h$, $t = 8.6 s$; (e) $H = 0.2 h$, $t = 8.6 s$; (f) $H = 0.8 h$, $t = 8.6 s$. 
4.2. Effect of Excitation Amplitude on Sloshing in the Tank with a Vertical Baffle

The free surface elevation amplitude of unbroken sloshing waves in a non-baffled tank, normalized by the excitation amplitude, was independent of the excitation amplitude. In this section, the response of sloshing in a tank with a baffle to the excitation amplitude was investigated. The parameters were \( H = 0.8 \ h = 0.4 \ m, \ \omega = \omega_0, \ \Delta x = 0.01 \ m, \ \Delta z = 0.005 \ m \) and \( \Delta t = 0.002 \ s \). As shown in Figure 14, the same conclusion as in a non-baffled tank, the sloshing amplitude in a tank with a baffle, normalized by the excitation amplitude, did not vary with the excitation amplitude, when the wave steepness was small.

\[
\begin{align*}
\eta / A &= H = 0.0h - A = 0.0005m \\
\eta / A &= H = 0.0h - A = 0.002m \\
\eta / A &= H = 0.0h - A = 0.01m \\
\eta / A &= H = 0.8h - A = 0.0005m \\
\eta / A &= H = 0.8h - A = 0.002m \\
\eta / A &= H = 0.8h - A = 0.01m 
\end{align*}
\]

**Figure 14.** Time series of free surface elevation at \( y = 0 \) of sloshing in a tank without or with a vertical baffle under different excitation amplitudes.

4.3. Effect of Excitation Frequency on Sloshing in the Tank with a Vertical Baffle

A series of numerical experiments were conducted to investigate the response of baffle damping to excitation frequency. The parameters were \( H = 0.8 \ h = 0.4 \ m, \ A = 0.0005 \ m, \ \Delta x = 0.01 \ m, \ \Delta z = 0.005 \ m \) and \( \Delta t = 0.002 \ s \). It can be seen from Figure 15 that the baffle significantly changed the natural frequency of sloshing. There were two main peak frequencies, 0.775 \( \omega_0 \) and 1.8 \( \omega_0 \), which were both away from the lowest natural frequency of sloshing in the clean tank.

\[
\begin{align*}
\eta_{max} / A &= \text{present simulation} - H = 0.0h \\
\eta_{max} / A &= \text{analytical solution} \\
\eta_{max} / A &= \text{present simulation} - H = 0.8h 
\end{align*}
\]

**Figure 15.** The maximum free surface elevation at \( y = 0 \) of sloshing in a tank without (results of the present simulation and analytical solution of Faltinsen [34]) or with (results of the present simulation) a vertical baffle under different excitation frequencies.
4.4. Effect of Baffle Permeability on Sloshing

Porous medium model was adopted to simulate the permeable baffle. The height of the permeable baffle was \( H = 0.8 \) and \( h = 0.4 \) m. The position of the permeable baffle was the tank center. The response of the maximum free surface elevation to permeability coefficient \( \lambda \) of the baffle is shown in Figure 16. Other parameters were \( \omega = \omega_0 \), \( A = 5 \times 10^{-4} \) m, \( \Delta y = 0.01 \) m, \( \Delta z = 0.005 \) m and \( \Delta t = 0.005 \) s. As can be seen in Figure 16, the permeable baffles were more effective to suppress sloshing than the impermeable baffle. More importantly, there was a critical permeability coefficient of the baffle that was most effective in sloshing suppression. In these cases of sloshing in a tank with a permeable baffle, the critical permeability coefficient was about \( 2.43 \times 10^{-5} \) m/s. The suppression of the permeable baffle on sloshing became stronger as the baffle permeability coefficient (\( \lambda \)) increased when \( \lambda \) was less than the critical permeability coefficient but became weaker as \( \lambda \) increased when \( \lambda \) was larger than the critical permeability coefficient. The time series of free surface elevations at the left tank wall under a different permeability coefficient are shown in Figure 17. The second plot in Figure 17 was the result of the critical permeability coefficient.

![Figure 16. The maximum elevation of free surface at \( y = 0 \) of sloshing under different baffle permeability coefficients (the unit of permeability coefficient \( \lambda \) is m/s).](image)

Maximum fluid velocity is presented to further investigate the effect of the permeability of the baffle on sloshing. In Figure 18, the velocities of the fluid in a tank with a permeable baffle along the water depth were much smaller than those in a tank with an impermeable baffle (Figure 12). The maximum velocity along the water depth occurred at the region of baffle tip, when the permeability coefficient was smaller than the critical permeability coefficient. The velocities along the water depth became smallest under the critical permeability coefficient. However, when the permeability coefficient was sufficiently large, the velocities at the tank center became large, especially at locations below the baffle tip. The maximum velocity occurred not at the free surface or baffle tip, but below the baffle tip under a sufficiently large permeability coefficient.
Figure 17. The time series of free surface elevation at $y = 0$ of sloshing under different baffle permeability coefficients (the unit of $\lambda$ is m/s).

Figure 18. The vertical distribution of the maximum velocity at the tank center of sloshing under different baffle permeability coefficients. (a) Horizontal component of velocity; (b) Vertical component of velocity. (the unit of $\lambda$ is m/s).

Figure 19 shows a comparison of fluid velocity fields in the tank without a baffle, with an impermeable baffle and with a permeable baffle at different times. Under a large permeability coefficient, the maximum velocities occurred not only at the free surface and the baffle tip, but also in other regions of the baffle and at the bottom of the tank. Furthermore, as shown in Figure 19i,j, the vortices can also be observed throughout the flow field as the permeability coefficient of the baffle increased. Therefore, Figure 20 is presented to exhibit the different velocity field under a large permeability coefficient $\lambda = 0.098$ m/s in detail. The velocities in a tank with a baffle of a large permeability coefficient were even larger than those in a clean tank. Under a permeability coefficient of
\( \lambda = 0.098 \text{ m/s} \), the maximum velocities and the vortices were first observed at the lower half of the baffle. With time, the vortices were gradually observed at the tank bottom, the tank walls, the free surface and the upper half of the baffle. The velocity field became complicated.

\[ \text{(a) Non-baffle, } t/T_0 = 4.90 \]
\[ \text{(b) Non-baffle, } t/T_0 = 7.27 \]
\[ \text{(c) Impermeable baffle, } t/T_0 = 4.90 \]
\[ \text{(d) Impermeable baffle, } t/T_0 = 7.27 \]
\[ \text{(e) } \lambda = 9.8 \times 10^{-6}, t/T_0 = 4.90 \]
\[ \text{(f) } \lambda = 9.8 \times 10^{-6}, t/T_0 = 7.27 \]
\[ \text{(g) } \lambda = 2.43 \times 10^{-5}, t/T_0 = 4.90 \]
\[ \text{(h) } \lambda = 2.43 \times 10^{-5}, t/T_0 = 7.27 \]

Figure 19. Cont.
The fluid velocity fields of sloshing in the tank without a baffle, with an impermeable baffle, and with a permeable baffle at different time instants. (a) Non-baffle, $t/T_0 = 4.90$; (b) Non-baffle, $t/T_0 = 7.27$; (c) Impermeable baffle, $t/T_0 = 4.90$; (d) Impermeable baffle, $t/T_0 = 7.27$; (e) $\lambda = 9.8 \times 10^{-5}$, $t/T_0 = 4.90$; (f) $\lambda = 9.8 \times 10^{-6}$, $t/T_0 = 7.27$; (g) $\lambda = 2.43 \times 10^{-5}$, $t/T_0 = 4.90$; (h) $\lambda = 2.43 \times 10^{-5}$, $t/T_0 = 7.27$; (i) $\lambda = 0.098$, $t/T_0 = 4.90$; (j) $\lambda = 0.098$, $t/T_0 = 7.27$. (unit of $\lambda$ is m/s).

Figure 20. Cont.
Figure 20. The fluid velocity fields of sloshing under the permeability coefficient $\lambda = 0.098$ m/s at different time instants. (a) $t/T_0 = 2.70$; (b) $t/T_0 = 3.90$; (c) $t/T_0 = 5.50$; (d) $t/T_0 = 8.92$; (e) $t/T_0 = 14.00$; (f) $t/T_0 = 24.50$; (g) $t/T_0 = 25.00$; (h) $t/T_0 = 33.80$.

5. Conclusions

Numerical simulations were conducted to investigate the effects of a vertical impermeable and a vertical permeable baffle on sloshing. The results show that baffles significantly changed the natural frequency of sloshing. The sloshing became weaker as the baffle height increased when the baffle height did not exceed 80% of the water depth. The time required for the free surface wave to reach stability became shorter as the baffle height increased. Similar to the results in non-baffled tank, the sloshing response in the tank with a baffle, normalized by the excitation amplitude, was independent of the excitation amplitude when the wave steepness was small. In the tank with a vertical baffle of height $H = 0.8 h$ there were two peak frequencies in response of sloshing to excitation frequency, which were both away from the lowest natural frequency of sloshing in the clean tank.

The permeable baffle was effective to suppress sloshing. There was a critical permeability coefficient of the baffle that was most effective to suppress sloshing. In addition, the maximum fluid velocities in the tank with a baffle of a sufficiently large permeability coefficient were larger than those in a tank with an impermeable baffle. The maximum velocities appeared over the entire area of the baffle, the bottom and walls of the tank, not only at the free surface (sloshing in a non-baffled tank) or the baffle tip (sloshing in a tank with a vertical impermeable baffle). The vortices appeared not only at the baffle tip (sloshing in a tank with a vertical impermeable baffle), but also throughout the entire region of the baffle, the bottom and walls of the tank and the free surface. The distribution of maximum flow velocity and vorticity may be beneficial to abate the stratification of the non-uniform fluid mixtures. In the future, experiment investigations will be conducted to obtain a comprehensive acquaintance on sloshing in a tank with a permeable baffle.

Author Contributions: Conceptualization, L.Y. and M.-A.X.; validation, L.Y. and A.Z.; writing and editing, L.Y. and M.-A.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Fundamental Research Funds for the Central Universities (2017 B697 X14 and B200202055), Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX17_0449) and the National Natural Science Foundation of China (No. 51679079).

Conflicts of Interest: The authors declare no conflict of interest.

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