Numerical Investigation on the Collision between a Solitary Wave and a Moving Cylinder

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Abstract: A 2-D numerical wave tank (NWT) was applied for solving the interaction between a solitary wave and a moving circular cylinder. The cylinder was placed at various positions from the tank bed floor. The cylinder can move at a constant horizontal velocity towards the solitary wave. The collision between a solitary wave and a moving cylinder is investigated at various conditions. A total of fifteen cases were studied. Ten different numerical simulations were used, including five submergence depths and two different moving velocities. The other five different numerical simulations were studied when the cylinder was unmoved in the NWT for comparing wave-structure interaction results between the moving and unmoved cylinders. The numerical results were obtained by calculating Reynolds-Averaged Navier-Stokes (RANS) equations and the volume of fluid (VOF) equations. Two different codes (User-Define-Function-UDF) were used for the generation of a solitary wave by moving a wave paddle and traveling cylinder in the NWT. The dynamic mesh method was applied for recreating mesh. First, the ability of CFD codes to generate a solitary wave by using wave paddle movement and the hydrodynamic forces of a moving cylinder were validated by numerical results. Further, the free-surface elevation and hydrodynamic forces were considered at various conditions. The numerical results show that moving cylinder velocity and the space between the cylinder and the tank bed floor have significant effects on surface displacement and hydrodynamic forces.

Keywords: wave-structure interaction; solitary wave; hydrodynamic forces; computational fluid dynamics (CFD)

1. Introduction

The numerical solving of wave interaction with a moving body is of great use in ocean engineering applications, such as for ships or submarines traveling against waves. An investigation of wave–structure interaction can help us understand the hydrodynamic forces between a wave and a moving body. Studies on the wave–structure interaction have many benefits in the design of ships, submarines, and ocean structures. Lin [1] studied a new two-dimensional fixed-grid model for the simulation of free-surface flow interaction with a moving body. He used the Lagrangian method for body motion and the Eulerian method for solving fluid motion around a moving body. He simulated some important problems in ocean engineering, such as the generation of a solitary wave, water exit, and water impact. The results showed that the new model can solve complex problems with good accuracy. A multiple-layer σ-coordinate model was developed by Lin [2]. The model was applied for solving wave–structure interaction problems. The solitary wave interaction with a rectangular obstacle was tested by this model at three various submergence depths. Solitary wave generation by the wave
paddle movement was carried out experimentally and numerically by Wu et al. [3]. They studied
behaviors of solitary waves under different conditions, such as still water depth, and the speed of the
paddle. Various solutions of solitary waves were considered numerically by Wu et al. [4]. They tested
four solitary wave solutions, including Boussinesq, Rayleigh, Grimshaw, and Fenton. Various wave
paddle motions were created by using these models, and numerical solitary waves were simulated in a
2-D NWT. Luo et al. [5] used the Consistent Particle Method (CPM) to study a solitary wave impact on
a seawall. It was a parametric study of geometry and wave height. Wave impinging and overtopping
were tested with various geometries and wave heights. A new numerical method was utilized for
modeling the solitary wave interaction with a bottom-mounted barrier by Wu et al. [6]. The volume
of fluid model (VOF) was solved in the Reynolds-Averaged Navier–Stokes (RANS) equations with a
k-epsilon turbulent model. The model was able to solve 2-D numerical problems. A Boussinesq Model
was employed for the simulation of the solitary wave run-up zone over back-reef slopes by Liu et al. [7].
The effects of slope angle, reef flat width, and water depth over the reef flat were presented in this study.
Ren et al. [8] studied the solitary wave interaction with a submerged breakwater by using the Consistent
Particle Method (CPM). Profiles of the wave were obtained when a solitary wave acted on a submerged
breakwater. You et al. [9] investigated the interaction between solitary waves and a submerged flat
plate at three submergence depths of the flat plate and four solitary wave heights. The relation between
hydrodynamic forces and other parameters was considered in this study. Seiffert et al. [10] considered
solitary wave interaction with a flat plate in a 2-D NWT. Horizontal and vertical forces were obtained
using Open-FOAM commercial software in this study. The interaction between a solitary wave and
a submerged horizontal plate was investigated numerically by Lo et al. [11]. The vertical force on
a submerged horizontal plate was calculated at two different depths. The interaction between a
solitary wave and a thin submerged plate was studied by Chang et al. [12]. Various inclinations of
the submerged plate were presented numerically and experimentally. Particle image velocimetry
(PIV) and stream function-vorticity formulations with the free surface (SVFS) model were used for the
experimental method and numerical model. The interaction between a solitary wave and a coastal
bridge was studied numerically and experimentally by Hayatdavoodi et al. [13]. They investigated
many different parameters, such as water depth, submergence depth, and wave amplitude. The CFD
program Open-FOAM was applied for solving wave-induced forces on a bridge. The coastal bridge
deck with girders was studied numerically by Xu et al. [14]. They employed Ansys commercial software
for solving RANS equations with the k-omega turbulence model in this numerical study. The solitary
wave forces on a coastal bridge deck were investigated by Moideen et al. [15]. The effects of the girder
spacing and girder depth were considered on a coastal bridge deck. The results revealed that the peak
vertical impact force depends on these parameters. The interaction between waves and a submerged
cylinder was pursued experimentally and numerically by Tian et al. [16]. The hydrodynamic force of
the cylinder was computed in a 3-D numerical wave tank (NWT) by using Ansys-Fluent commercial
software. Loh et al. [17] used Open-FOAM commercial software for simulating the interaction between
waves and a semi-immersed horizontal cylinder. Hydrodynamic forces were investigated for a
semi-immersed horizontal cylinder at different types of wave conditions. Hu et al. [18] studied the
interaction between waves and a circular cylinder during the submergence process. The volume of
fluid method was solved by using Ansys-Fluent commercial software in a 2-D NWT. Hydrodynamic
forces on the circular cylinder were computed during the submergence process. The smoothed particle
hydrodynamics (SPH) numerical model was applied for analyzing a solitary wave hitting a horizontal
circular cylinder placed at half of the water depth by Aristodemo et al. [19]. They calculated horizontal
and vertical hydrodynamic forces on a submerged horizontal cylinder, and results were compared to
other numerical and experimental studies. Tripepi et al. [20] considered tsunami-like solitary wave
interaction with a horizontal circular cylinder located on a rigid sea bed. The horizontal and vertical
hydrodynamic forces on the horizontal circular cylinders were obtained using the experimental setup.
They carried out 30 laboratory tests in a wave flume. The results show that the height of positive
horizontal peaks and positive vertical peaks depend on the value of A/d. If A/d < 0.105, the positive
horizontal peaks are greater than the positive vertical peaks. If A/d > 0.105, the positive vertical peaks are greater than the positive horizontal peaks. Aristodemo et al. [21] studied the interaction between solitary waves and a circular cylinder experimentally and numerically. They studied the horizontal and vertical hydrodynamic forces on horizontal circular cylinders located near a rigid horizontal bed. The effects of gap-to-diameter ratios were investigated in this study. Zhao et al. [22] presented a two-dimensional numerical study on the hydrodynamics of submarine pipelines. The effects of wave height, water depth, and pipeline diameter on the hydrodynamic characteristics of submarine pipelines were investigated by using a real-world tsunami wave and a solitary wave. Ong et al. [23] carried out 2-D numerical simulations of waves passing two semi-submerged horizontal circular cylinders in tandem. The k-ω turbulence model was used for solving the turbulent flow in the numerical tank. The vertical hydrodynamic forces were investigated on the cylinders at different spacings between the two cylinders. Olcay et al. [24] studied the locomotion of squid under numerical and experimental conditions. They obtained the hydrodynamic force and pressure distribution. They employed DPIV measurements for experimental models and Ansys Fluent computational fluid dynamics software for the numerical model. A numerical study was carried out for simulating the movement of squid traveling in water by Tabatabaei-Malazi et al. [25]. Drag forces and drag coefficients were obtained at various squid locomotion speeds. They used the SST k-w turbulence model for solving the fluid domain. Underwater locomotion of squid was investigated numerically by Olcay et al. [26]. A 3-D model of squid was simulated by Ansys Fluent computational fluid dynamics software and also the realizable k-ε turbulence model was employed for simulation. Drag and lift forces were obtained for different angles of attack, funnel diameters, and Reynolds numbers. Tabatabaei-Malazi et al. [27] numerically simulated squid travel acceleration. Two different velocity programs were utilized for moving. UDF programs were used in Ansys fluent computational fluid dynamics software. The effect of acceleration on hydrodynamic forces was calculated at all bodies. The hydrodynamics forces of a circular cylinder close to a wall were considered by Tong et al. [28]. They used the large eddy simulations (LES) method for the simulation of flow over a 3-D circular cylinder near a wall. Drag forces and pressure distributions were obtained on the cylinder.

In this study, a two-dimensional cylinder with and without moving was investigated in the NWT to understand the horizontal and vertical forces on the cylinder at various positions and two different horizontal moving velocities. Commercial CFD code-Fluent was applied to model the 2D NWT. A piston-type wave-maker, which was placed at the left side of the domain, was used for generating a solitary wave. Two different UDF codes were used for the motion of the wavemaker and cylinder in the NWT. Firstly, the numerical codes to generate waves and cylinder motions in NWT were validated against other numerical solutions to check the accuracy and capability of the codes. Furthermore, five different models of cylinder position were defined and solved in two various moving velocities. The generation of a solitary wave, free surface elevation during the wave-structure interaction, and horizontal and vertical forces acting on the cylinder were obtained. The paper was organized as follows: Section 2 defines governing equations, numerical methods, generation of a solitary wave, validation of a solitary wave, and validation of hydrodynamic forces. Section 3 presents numerical results and discussions. Section 4 contains the conclusions.

2. Numerical Method

2.1. Governing Equations

In this study, a two-dimensional numerical model is used which includes water and air in the computational domain. Water and air are separated by a free surface boundary. The RNG k-ε turbulence model is applied for the turbulent flow simulation (Tina et al. [16] and ANSYS Fluent Theory Guide [29]). The governing equations representing the continuity and momentum formulas are as given below:

\[
\frac{\partial p}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]
were studied a constant wave height and water depth. In other words, the ten numerical simulations
where \( k \) is the external source term, and \( R_e \) is a turbulence model:

\[
\frac{\partial (pk)}{\partial t} + \frac{\partial (pku_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \alpha_k \mu_{eff} \frac{\partial k}{\partial x_i} \right] + G_k + b_k - \rho \varepsilon - Y_M + S_k
\]

(3)

where \( k \) is the turbulent kinetic energy and \( \varepsilon \) is the rate of dissipation, \( G_k \) is turbulence kinetic energy generation due to the average velocity gradient, \( b_k \) is turbulent kinetic energy generation due to buoyancy, \( Y_M \) is fluctuating dilatation involvement in the overall dissipation rate, \( S_k \) is a user-defined source term, and \( R_e \) is a term in the \( \varepsilon \) equation. The model constants for the RNG \( k-\varepsilon \) turbulence model are \( C_{1k} = 1.42 \), \( C_{2k} = 1.68 \), and \( C_{\mu} = 0.09 \).

The VOF method is used to solve free surface deformation (Shen et al. [30]). The volume fraction of the phase \( \alpha \) is determined in the computational cell. This means that if \( \alpha = 0 \), the cell is empty of fluid. If \( \alpha = 1 \), the cell is full of fluid. If \( 0 < \alpha < 1 \), the cell contains the interface between water and air. The primary-phase volume fraction can be calculated based on the following constraint:

\[
\sum_{q=1}^{n} \alpha_q = 1
\]

(5)

The two-dimensional continuity equation for the volume fraction is inscribed in Equation (6):

\[
\frac{\partial \alpha_i}{\partial t} + u \frac{\partial \alpha_i}{\partial x} + v \frac{\partial \alpha_i}{\partial y} = 0
\]

(6)

2.2. Numerical Wave Tank (NWT)

The schematic diagram of the two-dimensional (2-D) numerical wave tank (NWT) is represented in Figure 1. The overall size of the NWT is 100 m long and 2m deep. The solitary wave is generated by a piston-type wave-maker and is located on the right side of the numerical wave tank (NWT). A cylinder that has a diameter \( D = 0.3 \) m is located at a distance of about 50 m from the paddle, and the cylinder includes five different spaces between the cylinder and the tank bed floor (\( M = 0.85 \) m, \( 0.80 \) m, \( 0.75 \) m, \( 0.70 \) m, and \( 0.65 \) m). The cylinder has five different spaces from the tank bed floor, so five different cylinder models are defined as \( M = 0.85 \) m (model 1), \( M = 0.80 \) m (model 2), \( M = 0.75 \) m (model 3), \( M = 0.70 \) m (model 4), and \( M = 0.65 \) m (model 5). The wave height of the solitary wave is \( H = 0.1 \) m with a constant water depth \( h = 1 \) m in the NWT. The no-slip wall condition is chosen at the tank bed floor and cylinder wall. The top boundary is defined as a pressure-inlet so air can enter or leave the domain. The right boundary is defined as a pressure-outlet. Two different UDF codes are applied in this study. One is used for a piston-type wave-maker motion and the other is used for a moving cylinder. The cylinder can move at two different constant horizontal velocities \( U_c = 0.1 \) m/s and 0.05 m/s. The cylinder moves in the negative \( x \)-direction and the solitary wave moves in the positive \( x \)-direction, so the solitary wave and moving cylinder hit together in the NWT (they move in the opposite direction). The present study only focused on understanding the interaction between a solitary wave and a moving cylinder at various conditions. The interaction between a solitary wave and an unmoved cylinder was also studied for comparing results. A total of 15 cases were studied a constant wave height and water depth. In other words, the ten numerical simulations include the interaction between a solitary wave and a moving cylinder at two different constant
horizontal velocities, and five numerical simulations include the interaction between a solitary wave and an unmoved cylinder. Details of the cylinder models were respectively illustrated in Figure 2. The summary of all numerical simulations was represented in Table 1.

![Figure 1. Schematic diagram of the numerical wave tank (NWT).](image)

![Figure 2. Detail of the models (close up of the cylinder).](image)

| Wave Height $H$ (m) | Water Depth $h$ (m) | Moving Cylinder $U_c = 0.1$ m/s | Moving Cylinder $U_c = 0.05$ m/s | Motionless Cylinder $U_c = 0$ m/s |
|---------------------|---------------------|-------------------------------|-------------------------------|-------------------------------|
| 0.1                 | 1                   | Model 1                        | Model 1                        | Model 1                        |
| 0.1                 | 1                   | Model 2                        | Model 2                        | Model 2                        |
| 0.1                 | 1                   | Model 3                        | Model 3                        | Model 3                        |
| 0.1                 | 1                   | Model 4                        | Model 4                        | Model 4                        |
| 0.1                 | 1                   | Model 5                        | Model 5                        | Model 5                        |

2.3. Spatial and Temporal Discretization

Triangle and quadrilateral elements were employed for the meshing solution domain. The multi-block mesh configuration method was used, and the solution domain was subdivided into...
different regions. Triangle mesh was applied around the cylinder with high-density mesh because the
dynamic mesh was used for the simulation moving cylinder and the quadrilateral mesh was used for
other parts of the computational domain. A total of 130–175 thousand elements were used for five
various models (with and without moving) at the solution domain, as shown in Figure 3.

![Figure 3](image_url)

**Figure 3.** (a) The computational mesh of the solution domain; (b) an enlarged view around the
cylinder surface.

The minimum time step is calculated using the Courant-Friedrichs-Lewy (CFL) condition to
obtain a good numerical convergence. \( \Delta t \) can be computed:

\[
\frac{u \Delta t}{\Delta x} \leq C
\]

where \( u \) is the maximum characteristic velocity in the fluid domain, \( \Delta x \) is the minimum cell size, and
\( C \) is the Courant number. The Courant number is selected to be 0.25 for the VOF model. We chose
\( \Delta t = 0.005 \text{s} \) to achieve good numerical stability in this study. All simulations were implemented on a
Core i7-7700 HQ 2.80 GHz CPU, 16 GB RAM running Windows 10. Table 2 shows the computational
time of models for 5000 time steps (\( t = 25 \text{s} \)).

| Models   | Motionless Cylinder | Moving Cylinder \( U_c = 0.05 \text{ m/s} \) | Moving Cylinder \( U_c = 0.1 \text{ m/s} \) |
|----------|---------------------|---------------------------------------------|---------------------------------------------|
| Model 1  | 19 h (129,194 mesh elements) | 26 h (151,988 mesh elements) | 33 h (172,960 mesh elements) |
| Model 2  | 19 h (129,194 mesh elements) | 26 h (151,988 mesh elements) | 33 h (172,960 mesh elements) |
| Model 3  | 19 h (129,194 mesh elements) | 26 h (151,988 mesh elements) | 33 h (172,960 mesh elements) |
| Model 4  | 19 h (129,194 mesh elements) | 26 h (151,988 mesh elements) | 33 h (172,960 mesh elements) |
| Model 5  | 19 h (129,194 mesh elements) | 26 h (151,988 mesh elements) | 33 h (172,960 mesh elements) |

2.4. Generation of Solitary Wave and its Validation

A solitary wave was produced by a wave paddle movement at a constant water depth. The performance of the generation of a solitary wave in Lin [1,2] was utilized in the present study, and validation was carried out. The paddle motion can be given as follows:

\[
u[x(t), t] = \frac{c \eta}{h + \eta}\]

where \( u \) is the paddle velocity and \( \eta \) is the free surface displacement that is defined as:

\[
\eta[x(t), t] = H \text{sech}^2 \left\{ \frac{3H}{4h^3} [x(t) - ct + x_0] \right\}
\]
where $H$ is wave height, $h$ is still water depth, $x_0$ is the distance between the origin and wave crest at $t = 0$, $x(t) = \int_0^t u \, dt$ is the place of the paddle at time $t$, $c = \sqrt{g(h + H)}$ the phase velocity of the wave, and $g$ is the gravitational acceleration.

We used a UDF for paddle movement according to the above equations, and the dynamic mesh method was applied for mesh deformation. The solitary wave has a wave height $H = 0.1$ m and constant water depth $h = 1$ m. The computational domain is $100 \, \text{m} \times 2 \, \text{m}$. A uniform mesh with $\Delta x = 0.1$ m and $\Delta y = 0.01$ m was applied by using a constant $\Delta t = 0.02$ s. Figures 4 and 5 show the comparison of the time history of the free-surface elevation at various locations between the present study and Lin [2].

![Figure 4](image1.png)

**Figure 4.** A comparison of the time history of the free-surface elevation at $x = 10.0$ m between the present study (solid line) and the Lin [2] study (circle).

![Figure 5](image2.png)

**Figure 5.** A comparison of the time history of the free-surface elevation at $x = 52.7$ m between the present study (solid line) and the Lin [2] study (circle).

### 2.5. Hydrodynamic Forces and Validation of a Moving Cylinder

A cylinder can experience hydrodynamic forces when it moves in a fluid (Olcay et al. [26], Batchelor [31], and Vasudev et al. [32]). Hydrodynamic forces on the cylinder can be computed by using:

\[
F_{\text{Horizontal force}} = F_{D, \text{pressure}} + F_{D, \text{viscous}} = \oint P h \, \delta dS + \oint \tau_w \, \delta dS \\
F_{\text{Vertical forces}} = F_{L, \text{pressure}} + F_{L, \text{viscous}} = \oint P h \, \delta dS + \oint \tau_w \, \delta dS
\]

(10)

(11)

where $F_{D, \text{pressure}}$ and $F_{D, \text{viscous}}$ are drag forces in the x-direction due to the pressure and viscous effects, respectively. Similarly, $F_{L, \text{pressure}}$ and $F_{L, \text{viscous}}$ are lift forces in the y-direction because of the pressure and viscous effects, respectively. Here, $p$ is the pressure on the cylinder, and $\tau_w$ is the wall shear stress on the surface of a cylinder.

A UDF code is employed for moving a cylinder in the NWT. The cylinder can move in horizontal and vertical directions, and the dynamic mesh method is used for recreating mesh around the cylinder.
The setup of the numerical model is the same used by Lin [1]. The radius of the cylinder is 1 m ($R = 1$ m). The initial distance between the center of the cylinder and the still water surface is 1.25 m. The gravitational acceleration is $9.8 \text{ m/s}^2$ ($g = 9.8 \text{ m/s}^2$). The cylinder moves downwards with a constant velocity $V = 3.13 \text{ m/s}$. Figure 6 shows the time histories of fluid forces on the cylinder. It can be seen from Figure 6 that the total vertical force is almost constant when the cylinder is completely inside the water. Here, the total vertical force includes the drag force and buoyancy force. The horizontal force is nearly zero because the cylinder moves in the vertical direction, and also its shape is symmetrical. Figure 7 shows free surface deformation when the cylinder is in motion. It is clearly illustrated that good agreements are obtained between the results of the present numerical model and Lin’s numerical models.

Figure 6. A comparison of the time history of the fluid forces on the cylinder between the present study (solid line) and the Lin [1] study (x).

Figure 7. Snapshots of moving cylinder interaction with a free surface flow (a) $t = 0.0 \text{ s}$, (b) $t = 0.25 \text{ s}$, (c) $t = 0.375 \text{ s}$, (d) $t = 0.435 \text{ s}$.
3. Results and Discussion

3.1. Hydrodynamic Forces

The horizontal and vertical hydrodynamic forces induced by a solitary wave on a moving cylinder at two different velocities are calculated for all five models. The acting of the horizontal and vertical hydrodynamic forces is also investigated when the cylinder does not move. The horizontal and vertical forces on the cylinder are obtained from surface integration of the pressure and viscous effects, including hydrodynamic pressure, hydrostatic pressure, and shear stresses.

In Figures 8–12, comparisons were made for the time histories of horizontal forces for all models (model 1, model 2, model 3, model 4, and model 5) in various conditions. Comparisons were carried out between moving cylinders at two different horizontal velocities ($U_c = 0.05$ m/s and $0.1$ m/s) and an unmoved cylinder (red line) for all models. Horizontal forces have a similar orientation at all simulations. The horizontal force peaks for all models are similar to each other. Two peaks are created in the horizontal forces during the solitary wave interaction with the cylinder, and the directions of peaks are the opposite, including a positive peak and a negative peak. In the present study, the maximum positive horizontal force is the Positive Force (PF) and the minimum negative horizontal force is the Negative Force (NF). The solitary wave energy decreases when the solitary wave arrives at the cylinder. The decreasing wave energy depends on the moving cylinder velocity and the space between the cylinder and the tank bed floor. The horizontal force on the unmoved cylinder is always smaller than the horizontal force on the moving cylinder for each model. It is easy to realize that two horizontal forces combine with each other when the cylinder moves in the NWT. One is the horizontal forces from the solitary wave, and the other is the horizontal forces from the moving cylinder. In other words, when the cylinder is motionless, only the horizontal force from the solitary wave acts on the cylinder. Maximum horizontal forces are obtained in model 2 (Figure 9) for the moving and unmoved cylinders because the height of the cylinder outside water is equal to the solitary wave height. In other words, the part of the wave impacting the cylinder is the wave crest, so it absorbs more wave energy, and also the cylinder can strongly discourage the velocity field of the solitary wave crest. It is also realized that the distinction between the positive force (PF) and negative force (NF) in model 2 is larger than the other models. Minimum horizontal forces occurred in model 5 (Figure 12) because it is completely under the free surface. The wave crest does not impact the moving cylinder directly, so the cylinder contains small wave energy in this condition. The negative horizontal force can be observed in all figures because the pressure gradient appears in front of the cylinder when the solitary wave passes the cylinder. The pressure gradient does not disappear quickly after the solitary wave passes the cylinder. Water moves to the negative pressure zone behind the cylinder, so it causes water reflux. Flow is enforced in the negative direction by the water reflux. The negative horizontal force is created when the negative flow acts on the cylinder. It is also found that the negative force (NF) of model 2 is nearly three times larger than the negative force (NF) of model 5 due to the space between the cylinder and the tank bed floor. It is noted that the horizontal forces have a large value when the cylinder start to move. This large value drops down quickly after a short time. The horizontal force of the unmoved cylinder is almost zero before and after acting on the solitary wave. The horizontal force of the unmoved cylinder increases when the solitary wave arrives at the cylinder. After the solitary wave passes the cylinder, the horizontal force of the unmoved cylinder reduces gradually. It is also realized that the horizontal force only contains the hydrodynamic force which is created by the horizontal velocity. It is also found that the effects of the horizontal force acting on the moving cylinder appear earlier than on the unmoved cylinder for all models. The cylinder moves towards the solitary wave, so contact between the solitary wave and the cylinder happens earlier. The positive and negative peaks of the horizontal forces are demonstrated in Figure 13. The positive forces of model 2 and model 3 are nearly the same, but the negative forces of model 2 are greater than model 3. Table 3 shows the time occurrence of the peaks of the horizontal forces when the surface wave crest passes the vertical section of the cylinder. Table 4 represents the percentage of difference between the maximum hydrodynamic...
forces acting on fixed and moving cylinders for all models. The percentage of difference between unmoved and moving cylinders with $U_c = 0.1 \text{ m/s}$ is always smaller than the percentage of difference between the unmoved and moving cylinders, with $U_c = 0.05 \text{ m/s}$ for each model.

Figure 8. The time variation of the horizontal forces for model 1. (a) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05 \text{ m/s}$. (b) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1 \text{ m/s}$.

Figure 9. The time variation of the horizontal forces for model 2. (a) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05 \text{ m/s}$. (b) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1 \text{ m/s}$.

Figure 10. The time variation of the horizontal forces for model 3. (a) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05 \text{ m/s}$. (b) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1 \text{ m/s}$. 
Figure 11. The time variation of the horizontal forces for model 4. (a) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05$ m/s. (b) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1$ m/s.

Figure 12. The time variation of the horizontal forces for model 5. (a) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05$ m/s. (b) A comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1$ m/s.

Figure 13. Positive and negative peaks of the horizontal forces for all models. (a) The positive force; (b) the negative force.
Table 3. The time occurrences of the peaks of the horizontal forces.

| Models   | Motionless Cylinder | Moving Cylinder $U_c = 0.05$ m/s | Moving Cylinder $U_c = 0.1$ m/s |
|----------|---------------------|----------------------------------|---------------------------------|
| Model 1  | Time = 18.64 s      | Time = 18.39 s                   | Time = 18.11 s                  |
| Model 2  | Time = 18.60 s      | Time = 18.32 s                   | Time = 18.08 s                  |
| Model 3  | Time = 18.37 s      | Time = 18.03 s                   | Time = 17.79 s                  |
| Model 4  | Time = 18.41 s      | Time = 18.16 s                   | Time = 17.92 s                  |
| Model 5  | Time = 18.31 s      | Time = 18.64 s                   | Time = 17.97 s                  |

Table 4. Percentages of maximum hydrodynamic force between unmoved and moving cylinders.

| Models   | (Moving Cylinder $U_c = 0.05$ m/s) & (Motionless Cylinder) | (Moving Cylinder $U_c = 0.1$ m/s) & Motionless Cylinder |
|----------|-------------------------------------------------------------|----------------------------------------------------------|
| Model 1  | 23.49%                                                      | 18.83%                                                    |
| Model 2  | 24.85%                                                      | 18.29%                                                    |
| Model 3  | 26.09%                                                      | 17.43%                                                    |
| Model 4  | 36.37%                                                      | 29.70%                                                    |
| Model 5  | 36.71%                                                      | 30.01%                                                    |

Figures 14–18 show the time histories of the vertical forces on the cylinder. It can be seen from the figures that the vertical forces have different behaviors in each model depending on the cylinder position. The vertical force includes the vertical hydrodynamic force and the hydrostatic force in the y-direction. The maximum vertical force depends on the space between the cylinder and the tank bed floor. The maximum vertical force increases when the space between the cylinder and the tank bed floor decreases. The vertical force is almost constant for a moving and unmoved cylinder before and after the passing wave, so the magnitude of the vertical force increases when the solitary wave arrives at the cylinder. When the cylinder moves along the horizontal direction, the buoyancy force is constant until the solitary wave impacts the cylinder. When the solitary wave arrives at the cylinder, the vertical force from the solitary wave and the buoyancy force combine. The buoyancy force is almost $F_b \approx 345$ N for model 1 (Figure 14) because half of the cylinder is outside of the free surface. After combining the buoyancy force and vertical force from the solitary wave in model 1, the total vertical force increases to 545 N. The buoyancy force is almost $F_b \approx 690$ N for model 5 (Figure 18) because the cylinder is completely underwater. After combining the buoyancy force and vertical force from the solitary wave in model 5, the total vertical force increases to 697 N. This shows that the effect of the solitary wave on model 1 is more than the effect on model 5. In other words, the part of the wave impacting the cylinder is the wave crest, so the cylinder can absorb more wave energy in model 1. The vertical forces of model 5 are greater than other models. It can be seen that the vertical force of the unmoved cylinder is larger than the moving cylinders in all models because the effect of the pressure gradient is great at the moving cylinders. It is also realized that the arrangements and figures of the peaks are different in the vertical force for each model. The figures of the peaks depend on the space between the cylinder and the tank bed floor. Model 1 has one peak because the part of the cylinder outside the water is higher than the solitary wave height, and also model 1 is the most effective for reducing wave energy. In model 2 (Figure 15), vertical forces have one peak, but the head of the peak is divided into two small parts. The height of the cylinder outside water is equal to the solitary wave height, so it creates two small parts in the head of the peak. The vertical forces have three peaks in model 4 (Figure 17) and model 5 (Figure 18). The first peak and second peak are larger than the third peak. In other words, the physical cause related to the three peaks is attributed to the influence of the vertical inertia component. The shape of the vertical force resembles that related to the vertical acceleration. The effect of the bottom is weak, and the lift force components are almost negligible. Table 5 shows the time occurrence of the peaks of the vertical forces when the surface wave crest passes the vertical section of the cylinder. Figures 19–23 show the time histories of hydrodynamic forces on the cylinder in the
vertical direction. In other words, the figures represent the vertical forces without hydrostatic forces on the cylinder. A big part of the vertical force includes the hydrostatic force in the vertical direction. Generally speaking, vertical forces and hydrodynamic forces have a similar tendency in this study.

**Figure 14.** The time variation of vertical forces for model 1. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05 \text{ m/s}$. (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1 \text{ m/s}$.

**Figure 15.** The time variation of vertical forces for model 2. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05 \text{ m/s}$. (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1 \text{ m/s}$.

**Figure 16.** The time variation of vertical forces for model 3. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.05 \text{ m/s}$. (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at $U_c = 0.1 \text{ m/s}$.
The time variation of vertical forces for model 4. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.05 \) m/s. (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.1 \) m/s.

The time variation of vertical forces for model 5. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.05 \) m/s. (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.1 \) m/s.

The time variation of the hydrodynamic forces for model 1. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.05 \) m/s. (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.1 \) m/s.
Figure 20. The time variation of hydrodynamic forces for model 2. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.05 \text{ m/s} \). (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.1 \text{ m/s} \).

Figure 21. The time variation of hydrodynamic forces for model 3. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.05 \text{ m/s} \). (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.1 \text{ m/s} \).

Figure 22. The time variation of the hydrodynamic forces for model 4. (a) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.05 \text{ m/s} \). (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.1 \text{ m/s} \).
with a moving cylinder is bigger than the solitary wave interacting with an unmoved cylinder. The results illustrate that the wave crest separates into two parts. One part of the flow returns upstream (backflow), and the other part moves downstream (forward flow). The height of the backflow increases and it acts on the cylinder because the cylinder moves to the wave. Moreover, the deformation of the solitary wave interacting with a moving cylinder and an unmoved cylinder have a similar tendency. The moving cylinder touches the solitary wave earlier than the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.05 \) m/s. (b) The comparison between the unmoved cylinder (red line) and the moving cylinder at \( U_c = 0.1 \) m/s.

Table 5. Time occurrences of the peaks of the vertical forces.

| Models   | Motionless Cylinder | Moving Cylinder \( U_c = 0.05 \) m/s | Moving Cylinder \( U_c = 0.1 \) m/s |
|----------|---------------------|---------------------------------------|----------------------------------|
| Model 1  | Time = 19.00 s      | Time = 18.59 s                        | Time = 18.38 s                   |
| Model 2  | Time = 18.59 s      | Time = 18.27 s                        | Time = 18.08 s                   |
| Model 3  | Time = 18.13 s      | Time = 17.83 s                        | Time = 17.49 s                   |
| Model 4  | Time = 17.86 s      | Time = 17.04 s                        | Time = 16.76 s                   |
| Model 5  | Time = 17.79 s      | Time = 17.51 s                        | Time = 17.18 s                   |

3.2. Deformation of Free Surface

The evolution of a solitary wave interacting with a moving cylinder and an unmoved cylinder is shown in Figures 24–27. The red color refers to the water phase, while the blue color refers to the air phase. Figure 24 presents the snapshots of cylinder-wave interaction for model 2 when the cylinder is motionless (unmoved cylinder) at various time points. Figure 24a–c show the solitary wave as it reaches the cylinder and the interaction between the solitary wave and the cylinder starts. The main wave crest separates into two parts. One part of the flow returns upstream (backflow), and the other part moves downstream (forward flow). The height of the backflow increases and it acts on the cylinder continually (Figure 24d,e), and then the height of the backflow decreases, and the forward flow has an interaction with the cylinder (Figure 24f,g). Two parts have a similar height at this moment time \( t = 20.5 \) s (Figure 24h). Figure 25 demonstrates the snapshots of cylinder-wave interaction for model 2 when the cylinder moves to the solitary wave (moving cylinder \( U_c = 0.1 \) m/s). The moving cylinder and the unmoved cylinder have a similar tendency. The moving cylinder touches the solitary wave earlier than the unmoved cylinder because it moves to the wave.

Figure 26 illustrates the snapshots of the cylinder-wave interaction for model 4 when the cylinder is motionless (unmoved cylinder) at various time points. The wave crest does not decompose, but it can be seen that the solitary wave has a small deformation. Figure 27 presents the snapshots of cylinder-wave interaction for model 4 when the cylinder moves to the solitary wave (moving cylinder \( U_c = 0.1 \) m/s). The moving cylinder and the unmoved cylinder have similar behaviors, but the moving cylinder arrives at the solitary wave earlier than the unmoved cylinder, and also the deformation of the wave crest in the moving cylinder is bigger than the unmoved cylinder. The results illustrate that the evolution of a solitary wave interacting with a moving cylinder and an unmoved cylinder has similar behaviors. The solitary wave and moving cylinder reach each other earlier than the unmoved cylinder because the cylinder moves to the wave. Moreover, the deformation of the solitary wave interacting with a moving cylinder is bigger than the solitary wave interacting with an unmoved cylinder.
Figure 24. Snapshot of evolution process of a solitary wave interacting with the unmoved cylinder for model 2; (a) $t = 17$ s, (b) $t = 17.5$ s, (c) $t = 18$ s, (d) $t = 18.5$ s, (e) $t = 19$ s, (f) $t = 19.5$ s, (g) $t = 20$ s, (h) $t = 20.5$ s.

Figure 25. Cont.
Figure 25. Snapshot of the evolution process of a solitary wave interacting with the moving cylinder $U_c = 0.1 \text{ m/s}$ for model 2. (a) $t = 17 \text{ s}$, (b) $t = 17.5 \text{ s}$, (c) $t = 18 \text{ s}$, (d) $t = 18.5 \text{ s}$, (e) $t = 19 \text{ s}$, (f) $t = 19.5 \text{ s}$, (g) $t = 20 \text{ s}$, (h) $t = 20.5 \text{ s}$.

Figure 26. Snapshot of the evolution process of a solitary wave interacting with the unmoved cylinder for model 4. (a) $t = 16.5 \text{ s}$, (b) $t = 17 \text{ s}$, (c) $t = 17.5 \text{ s}$, (d) $t = 18 \text{ s}$, (e) $t = 18.5 \text{ s}$, (f) $t = 19 \text{ s}$, (g) $t = 19.5 \text{ s}$, (h) $t = 20 \text{ s}$, (i) $t = 20.5 \text{ s}$, (j) $t = 21 \text{ s}$.
4. Conclusions

The interaction between a solitary wave and a cylinder was studied computationally at different cylinder velocities and spaces between the cylinder and the tank bed floor. The horizontal and vertical hydrodynamic forces induced by the solitary wave on a cylinder was calculated for various conditions. The horizontal and vertical forces increase when a solitary wave collides with a moving cylinder. Furthermore, the horizontal forces of interaction of a solitary wave with a moving cylinder are greater than the horizontal forces of interaction of a solitary wave with an unmoved cylinder. The horizontal and vertical forces strongly depend on cylinder velocity and the space between the cylinder and the tank bed floor. The vertical force increases when the space between the cylinder and the tank bed floor decreases because the hydrostatic force increases. The results demonstrate that the horizontal force of model 2 is greater than other models, and the vertical force of model 5 is greater than other models. The deformation of the solitary wave increases when the space between the cylinder and the tank bed floor increases. The volume of the fluid method (VOF) with the RNG $k-\varepsilon$ turbulence model is used to capture the free surface. It is clear from the present numerical study that wave-structure
interaction can be modeled accurately with the NWT method, which has the ability to simulate the stages of interaction between a solitary wave and a moving cylinder.

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