Effect of Inclination Angles on the Local Scour around a Submerged Cylinder

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Abstract: In ocean engineering and coastal environmental studies, local scour around a submerged structure is a typical issue, which is affected by the inclination of the structure. To investigate the effect of inclination directions and angles on flow structure and the bed morphology, a three-dimensional numerical model of a submerged inclined cylinder was established. In this model, the hydrodynamics are solved from the RANS (Reynolds-averaged Navier–Stokes) equations closed with the RNG k-ε turbulence model, while the bed morphology evolution is captured by the sediment transport model. In the case of vertical-cylinder scour, the simulation results agree well with existing laboratory experiments. In the cases of inclined-cylinder scour, the results show that the inclination direction not only changes the intensity and the location of the downflow but also modulates the pattern of the horseshoe vortex in front of the cylinder, thus influencing the local scour depth and the morphology of the bed. Compared with the case of vertical cylinder, the scour around an upstream-inclined cylinder is deeper, mainly due to the enhancement of downflow in front of the cylinder. The scour around a downstream-inclined cylinder is shallower and broader due to the weakened downflow and accelerated incoming flow. The maximum scour depth decreases with the inclination angle in the downstream-inclination case. In the upstream-inclination case, the maximum scour depth does not vary monotonously with the inclination angle, which results from a competitive effect of the horseshoe vortex and downflow in the front of the cylinder.

Keywords: underwater structure; inclined cylinder; downflow; local scour; stability

1. Introduction

Among the most prominent threats to the safety of the hydraulic structures in river/coastal/ocean areas is the local scour around their underwater pillar support, many of which are cylinders. When water flows past a bottom-mounted cylinder, the incoming flow boundary layer separates and the horseshoe vortex emerges in the front of the cylinder, while the wake vortices are formed behind the cylinder (Figure 1). These large-scale coherent structures (the downflow, horseshoe vortex, and the wakes vortices, etc.) increase the bed shear stress, causing the local scour [1–4]. The local scour might reduce the insertion depth of pile in the foundation, weaken the foundation’s bearing capacity, threaten the stability of a hydraulic structure and even lead to its failure.

In the context of bridge-pier protection, extensive studies are carried out on the flow features and the sediment-transport processes around an unsubmerged cylinder to capture the scour mechanism and to predict the scour depth for engineering applications [1,3,5–7]. It is found that the horseshoe vortex plays an important role in the forming of the scour hole. The circulation of the horseshoe vortex increases as the scour depth increases [1,4]. The time evolution of the size and the shape of the horseshoe was given by Unger and Hager [8]. The cylinder shape, the incoming velocity,
the Froude number, the Reynolds number and the thickness of boundary layer also play an important role in the flow fields around the cylinder, thus causing the variation of the scour hole [2,3,7,9–12].

With ocean exploration becoming deeper, the scour around the submerged obstacles, such as artificial reefs, detection equipment and suction caissons, have aroused wide concern in recent years. Sadeque and Loewen [13] compared the flow fields around submerged cylinders of varying height to an unsubmerged cylinder under the same incoming-flow condition. They found that in the submerged cases, the horseshoe vortex gets closer to the cylinder, and the submergence prevents the shedding of the wake vortices. Dey and Raikar [14] conducted a series of experiments to indicate that the increasing submergence ratio will reduce the hindrance of the cylinder, thus weakening the strength of the downflow and the horseshoe vortex, resulting in a shallower scour hole. Other studies show that the scour depth of a submerged cylinder is close to the scour depth of the unsubmerged case if the aspect ratio (the ratio of cylinder height to its diameter) is larger than 4 [15]. The scour depth becomes independent on the aspect ratio when this ratio drops below 2 [16]. Xie and Liang [17] indicated that for cylinders with low aspect ratio, local scour is restricted to the upstream side because a little vortex street exists in the wake. They also proposed an experimental method to reduce the time for the scour to reach its equilibrium. The effects of obstacle’s frontal area on the shape and depth of the scour hole were discussed by Euler and Herget [18] using a process-based analytical approach.

Besides the cases of vertical structures, the local scour around inclined structures also draws attentions from researchers in coastal/ocean engineering. Inclination occurs when the seabed near a structure’s bottom is eroded. Compared with their vertical counterparts, inclined structures present different features on the flow patterns, and the modification to scour holes need to be analyzed. By laboratory experiments, Bozkus and Yildiz [19] and Vaghefi and Ghodsian [20] indicated that the maximum scour depth decreases with the inclination angle of an unsubmerged cylinder. In the context of interactions between floods and riparian plants, Euler and Zemke [21] (2014) tried to capture the leading factor that affects the scour hole around an inclined cylinder. They found that the horseshoe vortex plays an important role when the inclination angle is small, while the wake vortices gradually dominate the scour as the inclination angle increases. The upward flow in the wake vortices close to the bed becomes stronger with an increasing inclination angle, as indicated by Kitsikoudis and Kirca [22] in their investigation for unsubmerged downstream-inclined cylinders.

The above studies show that submergence and inclination both play important roles in the local scour of a cylinder. However, the knowledge of their combined influence is limited and further research on the corresponding flow structures and scour patterns is required for applications in the
mangrove pneumatophore [23], artificial reefs [24,25], Fish and aquatic habitat [26], and the riparian plants [21], where a submerged inclined cylinder can be a valid simplified model.

In this paper, a numerical model based on the RANS equations along with a RNG (Renormalization-group) $k-\varepsilon$ turbulence model and a sediment transport model was established to investigate (1) the inclination effect on the flow structures around a submerged cylinder, (2) the scour patterns for different inclination directions and inclination angles and (3) the relationship between the inclination angle and the scour depth. Although in the coastal and ocean environment, the unsteady flow conditions (e.g., tides and waves) are dominated, only the steady flow condition is considered here to have a better comprehension on the scour mechanism around the inclined cylinder in the subsea condition, and present research will be extended to under the unsteady conditions and will be presented in our next study. As such, it is aimed at obtaining a better understanding of the flow and the clear-water scour around a submerged inclined cylinder.

2. Numerical Model

2.1. Governing Equations of the Flow

Considering the flow of an incompressible viscous fluid around a cylinder, the hydrodynamics are solved by the RANS (Reynolds-averaged Navier–Stokes) equations

$$\frac{\partial u_i}{\partial x_i} = 0$$

(1)

$$\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} + \frac{\partial \tau_{ij}}{\partial x_j}$$

(2)

where $x_i (i = 1, 2, 3)$ denotes the Cartesian coordinate component, $u_i$ denotes the velocity component in $x_i$ direction, $p$ denotes the pressure, $\nu$ denotes the kinematic viscosity, $t$ denotes the time, $\rho$ denotes the fluid density, and $\tau_{ij}$ denotes the Reynolds stress component defined as

$$\tau_{ij} = \nu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} k$$

(3)

in which $k$ is the turbulent energy, $\nu$ is the turbulent viscosity, $\delta_{ij}$ is the Kronecker delta.

The sediment transport simulation is sensitive to turbulence modeling [27], since the near-bed stresses are quite different for varies turbulence models. The RNG $k-\varepsilon$ model is quite successful in simulating low-turbulence-intensity flows in strong shear regions [28,29] and was, therefore, adopted in the present study. The governing equations of the RNG $k-\varepsilon$ turbulence model are:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ (\nu + \frac{\nu}{\sigma_k}) \frac{\partial k}{\partial x_j} \right] + C_{1k} \frac{\varepsilon}{k} \frac{\partial u_i}{\partial x_i}$$

(4)

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ (\nu + \frac{\nu}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{2\varepsilon} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial u_i}{\partial x_j} - C_{2\varepsilon} \rho \frac{\varepsilon \sigma_\varepsilon}{k}$$

(5)

in which $\varepsilon$ is the dissipation of turbulent energy, $C_{1k}, C_{2\varepsilon}, C_{2\varepsilon}, \sigma_k, \sigma_\varepsilon$ and $\sigma_\varepsilon$ are model coefficients whose values are usually set to 0.085, 1.42, 1.68, 0.7179 and 0.7179, respectively.

2.2. Sediment Transport Model

The bed near the cylinder is subjected to strong shearing actions. When the shear stress exceeds a critical value, the bed erosion occurs. This criterion can be expressed in dimensionless form

$$\theta \geq \theta_c, \quad \theta = \frac{\tau}{g \sqrt{d_0} (\rho_s - \rho)}$$

(6)
in which the Shields parameter $\theta$ is the nondimensionalized shear stress $\tau$, $g$ is the magnitude of the gravity acceleration, $\rho_s$ is the sediment density and $d_{50}$ is the median diameter of the sand grain. The critical Shields number $\theta_c$ can be calculated by a formula of Soulsby [30]

$$\theta_c = \frac{0.3}{1+1.2d_s} + 0.055 \left[ 1 - \exp \left( -0.02d_s \right) \right]$$

(7)

The nondimensional grain size $d_*$ is given by

$$d_* = d_{50} \left[ \frac{\rho (\rho_s - \rho)}{\mu^2} \right]^{\frac{1}{3}}$$

(8)

where $\mu$ is the fluid dynamic viscosity. The critical friction velocity $U_c$ can be calculated by the critical shear stress on bed $\tau_c$ when $\theta = \theta_c$

$$\tau_c = \rho U_c^2$$

(9)

At a sloping bed interface, the gravity applies a tangential component of force to make the sediment more or less stable depending on the incoming flow direction; thus, the $\theta_c$ in a sloping bed can be obtained by [30],

$$\theta_c = \frac{\cos \psi \sin \beta + \sqrt{\cos^2 \beta \tan^2 \phi_n - \sin^2 \psi \sin^2 \beta}}{\tan \phi_n}$$

(10)

where $\beta$ is the sloping angle of the bed surface, $\phi_n$ is the repose angle of the sediment and $\psi$ is the angle between the upslope direction and the incoming flow velocity adjacent to the sloping bed surface.

The transport rate of bedload can then be predicted by a model of van Rijn [31]

$$q_b = 0.053 d_{50}^{0.3} \left( \frac{\theta}{\theta_c} - 1 \right)^{2.1} \left[ g \left( \frac{\rho_s - \rho}{\rho} \right) d_{50}^3 \right]^{0.5}$$

(11)

The entrainment and the deposition are two opposing processes which take place at the same time. They are combined to control the net rate of the exchange between the bed material and the suspended load. For entrainment, the velocity at which the sediment leaves the bed surface can be calculated by the formula [32],

$$u_{en} = n \alpha_a d_{50}^{0.3} (\theta - \theta_c)^{1.5} \sqrt{g d (\rho_s / \rho - 1)}$$

(12)

where $\alpha_a$ is the entrainment coefficient, $n$ is the outward normal vector of the bed surface. In the deposition, the setting velocity of [30] is used,

$$u_{setting} = \frac{g \mu}{g \rho d} \left[ (10.36^2 + 1.049 d_{50}^{0.5}) - 10.36 \right]$$

(13)

The suspended sediment is transported by advection along with the fluid, and can be calculated by solving its own transport equation:

$$\frac{\partial C_s}{\partial t} + \nabla \cdot (u_s C_s) = \nabla \cdot (DC_s)$$

(14)

Here, $C_s$ is the suspended sediment mass concentration, which is defined as the sediment mass per volume of fluid-sediment mixture; $D$ is the diffusivity; $u_s$ is the suspended sediment velocity. Ignore the interactions between suspended load; the velocity difference between the suspended load and the fluid-sediment mixture is mainly the settling velocity of grains; $u_s$ is calculated by
where $\bar{u}$ is the velocity of the fluid-sediment mixture, which can be obtained by solving the continuity and the Navier–Stokes equations with the RNG $k$-$\varepsilon$ model.

3. Numerical Model Validation and Setup

3.1. Model Validation

To verify the accuracy of the present numerical model, two previous experimental results were selected to validate the hydrodynamic model and the sediment transport model, respectively.

A comparison of the simulation results with experimental results and the numerical results conducted by Roulund and Sumer [2] was chosen to investigate the accuracy of the hydrodynamic model. The experiment was conducted in a water flume, which was 35 m long and 3 m wide. The cylinder is surface-piercing (top of the pile is above the water surface) and was located in a smooth rigid bed, whose diameter was 0.536 m. The water depth was maintained at 0.54 m, the incoming velocity of the flow was 0.326 m/s during experiments and the flow was fully developed before reaching the cylinder; the numerical model adopted the $k$-$\omega$ model for turbulence closure and was coupled with a morphologic model to calculate local scour around a vertical cylinder, which was validated by the experiment data.

Figures 2 and 3 illustrate the validation of the horizontal velocity and vertical velocity in the plane of symmetry at different distances from the bed: there is a good agreement between the present simulation results and experimental results at the upstream side of the cylinder, although the velocities near the cylinder with small values of distances $(z = 0.5 \text{ cm} \text{ and } z = 1 \text{ cm})$ are underestimated. With the distance increase, this underestimation gradually disappeared $(z = 2 \text{ cm} \text{ and } z = 5 \text{ cm})$. At the downstream side of the cylinder, for the distribution of the vertical velocity, the present model shows good agreement with numerical results by Roulund and Sumer [2]; however, a discrepancy occurred between the numerical simulation results (both present results and previous results [2]) and experimental results for the horizontal velocity: the horizontal velocity was overestimated from $z = 0.5 \text{ cm} \text{ to } z = 5 \text{ cm}$.

Li and Yang [33] also selected this experiment [2] for the validation their model; however, the LES (large eddy simulation) turbulence model was adopted. From their results, the LES shows a better performance than RANS in the horizontal velocity validation, but there are still some inconsistencies in the downstream side for vertical velocity distribution. There is no clear explanation for the discrepancy as it also appeared in the previous studies [2,33–35]; this maybe attributed to the limitation of the turbulence model to describe the flow fields near the wall. Although there are some differences between the experiments and the present model, the results show that the present model has great potential in predicting the complex flow structures around a cylinder.

Experimental results performed by Khosronejad and Kang [12] were chosen to verify the accuracy of the sediment transport model. In their experiments, an unsubmerged cylinder ($D = 0.1651 \text{ m}$) was located in the center of a rectangular sandpit of 1.21 m width and 0.45 m depth, within a straight flume of 10 m long. The sandpit was 0.25 m deep and filled with noncohesive sediment whose median diameter was $d_{50} = 0.85 \text{ mm}$. Uniform water depth was maintained at 0.186 m corresponding to an inflow velocity of 0.25 m/s. The cylinder surface and flume side-walls were hydraulically smooth.

Figure 4 shows a good agreement between the calculated maximum scour depth ($d_s$) developed around the cylinder and the experimental results. The scour reached an equilibrium state after approximately 40 min; the maximum scour depth was 0.073 m, which is in accordance with the experiment results (0.076 m). The slight discrepancy is due to the different initial conditions. In the numerical simulation, the flow was fully developed before the sediment transport model begun to work, while in the lab experiments, the flow needed a few minutes to develop.
As seen from the above calibration, the present model is well validated, and we adopted it for the investigation of the local scour around the submerged inclined cylinder in the next section of this paper.

![Figure 2. Distribution of horizontal velocity (Vx) in symmetry plane (y = 0 m) at different distances from the bed.](image)
Figure 3. Distribution of vertical velocity ($V_z$) in symmetry plane ($y = 0$ m) at different distances from the bed.
Figure 4. Time evolution of maximum scour depth around the cylinder.

3.2. Model Domain

As shown in Figure 5, similar to the previous research [27,34], the numerical flume was set as 35 m long in the x-direction, 12 m wide in the y-direction and 4 m deep in the z-direction. The incoming velocity of the flow was $V = 2.5 \text{ m/s}$. During the simulation, the water depth $h$ was maintained at 2 m. The thickness of the bed was equal to 1 m, which was composed of a uniform and noncohesive sediments with a median grain size of $d_{50} = 5 \text{ mm}$ and density of $\rho_s = 2650 \text{ kg/m}^3$. The cylinder was located in the centerline of the computational domain and had a distance of 20 m from the inlet. The cylinder diameter was $D = 1 \text{ m}$. Considering the calculation efficiency and limited by the computer resources, 400 s was chosen in the present study: the detail of these parameters is summarized in Table 1.

Figure 5. Sketch of the computational domain, (a) side view; (b) top view.
Table 1. Model parameter.

| V (m/s) | h (m) | h_0 (m) | D (m) | D_50 (mm) | ρ_s (m^3/kg) |
|---------|-------|---------|-------|-----------|--------------|
| 2.5     | 2     | 1       | 1     | 5         | 2650         |

To investigate the influence of inclination directions on local scours around the submerged cylinder, six numerical cases were designed (Table 1). Case 1 and 2 are vertical cases. Case 3 and 4 are upstream inclined and Case 5 and 6 are downstream inclined. Table 2 shows the parameters of different cases and the inclination angle of the cylinder from −30° to 30° every 15° (negative values and positive values represent upstream inclined (UI) and downstream inclined (DI), respectively).

Table 2. Parameters of numerical cases.

| Case Number | h/m | α (°) |
|-------------|-----|-------|
| 1           | 3.0 | 0     |
| 2           | 1.0 | 0     |
| 3           | 1.0 | −30   |
| 4           | 1.0 | −15   |
| 5           | 1.0 | 15    |
| 6           | 1.0 | 30    |

3.3. Boundary Conditions

The proper boundary condition is important to obtain the accurate results for numerical simulation. In this study, five boundary conditions were chosen for different boundaries. For the inlet boundary, to be consistent with the steady current condition in the present study and ensure the developed flow condition at the flume inlet, the fully developed flow with the fixed velocity profile along the water depth was adopted, and the way in which we obtained the developed flow condition is similar to the previous studies [3,27]. The Froude number \( (Fr = V / \sqrt{gh}) \) in this study was 0.56, so the shear-free rigid lid hypothesis was not suitable here, the top boundary of the model was considered to be the standard atmospheric pressure and the VOF methods were adopted to capture the deformation of the air–water interface. For the bottom boundary, the wall boundary condition was considered, which applies the no-slip condition at the boundary. The symmetry boundary condition was complemented at the two lateral boundaries to apply a zero-gradient condition at the boundary as well as a zero-velocity condition normal to the boundary. The outflow boundary condition was employed at the outlet boundary where the gradient of the vectors was set to zero, which avoided the reflection of flow and overcame the limitation of physical dimensions.

3.4. Model Grids and Sensitivity Analysis of the Grid Size

The nonuniform structured grids were used to discretize the computational domain to save the computer resources and obtain accurate results. Finer grids were adopted near the cylinder and the bed surface for large velocity gradients. To explore the effect of the grid size on the numerical results, three grid sizes—Grid 1, Grid 2 and Grid 3—were tested. Take Grid 2, for example, to illustrate the variation of the grid size in the whole computational domain: the grid size of the inlet was 0.2D in the horizontal direction and gradually decreased to 0.05D around the cylinder to better capture the flow structure. In the vertical direction, the grid size was 0.05D near the bed surface and gradually transited to 0.15D at the water surface. The total number of cells was \( 1.74 \times 10^6 \). The details of the three grids are summarized in Table 3, and the sketch view of the grids near the cylinder for Case 2 is shown in Figure 6.
Table 3. Parameters of different grid.

| Grid Number | Total Cells | Minimum Mesh Size |
|-------------|-------------|-------------------|
| Grid 1      | $9.28 \times 10^5$ | 0.08D             |
| Grid 2      | $1.74 \times 10^6$ | 0.05D             |
| Grid 3      | $3.19 \times 10^6$ | 0.04D             |

Figure 6. The sketch view of the grids near the cylinder (Case 2), (a) top view; (b) side view.

The time evolution of maximum scour depth around the cylinder with three grid sizes is shown in Figure 7. It can be seen that the maximum scour depth calculated by Grid 1 was larger than the two other grid sizes, and the results calculated by Grid 2 and Grid 3 were approximately equal, which indicates that Grid 2 is sufficient to obtain the representative results. To save the computer resource, Grid 2 was chosen for all the next simulations.
Figure 7. Time evolution of maximum scour depth around cylinder with different grid size (Case 2).

4. Results and Discussion

4.1. Flow Fields in front of the Cylinder

The distribution of streamlines and the contour of $V_z$ at the symmetric plane ($y = 0$ m) in the initial scour process ($t = 0$ s) are presented in Figure 8. Due to the existence of the cylinder, the streamlines bend toward the bed, and the contour of the $V_z$ transited to the negative values in front of the cylinder. Compared to the unsubmerged cylinder (Figure 8a) with the submerged cylinder (Figure 8b), the downflow was delayed, and its strength and the ranges were weakened and reduced. This phenomenon was also found in previous experiments [14].

Figure 8. The contour of vertical velocity $V_z$ and streamlines around the cylinder in symmetry plane ($y = 0$ m) at $t = 0$ s, (a–f) represents Case 1 to Case 6 in Table 2, respectively.
Compared with the vertical cylinder, the inclination of the cylinder caused more complicated flow fields around the cylinder and altered the scour pattern subsequently. The upstream-inclined cylinders with the inclination angle of $\alpha = -30^\circ$ and $\alpha = -15^\circ$ are presented in Figure 8c,d, respectively. The upstream inclination led to the early meeting of the incoming flow and the cylinder, thus advancing the downward bend of the streamlines ($x = -1.4$ m, $x = -1.1$ m), compared with the vertical cylinder ($x = -0.9$ m) (Figure 8b). The range of the downflow is correspondingly larger. Figure 8c,d show the downstream-inclined cylinder with the inclination angle of $\alpha = 15^\circ$ and $\alpha = 30^\circ$, separately. The inclination led to a decrease in the resistance to the incoming flow; thus, the downward bend of the streamlines is closer to the cylinder ($x = -0.8$ m, $x = -0.7$ m), compared with the vertical cylinder (Figure 8b). The range of the downflow is correspondingly smaller.

Once the bed, shear stress induced by the horseshoe vortex exceeded the critical shear stress, the sediment was washed away by the incoming flow and the scour hole occurred around the cylinder. Figure 9 shows the streamlines and the contour of $V_z$ at $t = 320$ s around the cylinder in different conditions. The bed in front of the cylinder was eroded by the incoming flow. The scour depth was the deepest for the unsubmerged cylinder (Figure 9a). Compared with Figure 8, the range of the downflow was more extensive, and the curvature of the streamlines was more obvious. When the cylinder inclined to the upstream (Figure 9c,d), a distinct scour hole appeared in front of the cylinder. The curving streamlined almost parallel with the inclined cylinder, showing that the more violent downflow was formed at the upstream side of the cylinder. For the downstream-inclined cylinders (Figure 9e,f), the incoming flow remained undisturbed and streamlines run parallel with the bed until the flow encountered the upstream side of the cylinder. The strength of the downflow, the scour depth and the scope of the scour hole were smaller than the upstream-inclined cylinder.

Figure 10 shows the schematic view of the inclination effect on the velocity distribution in front of the cylinder. The profile of the incoming velocity in the vertical ($z$) direction was correlated with the logarithmic law. Due to the large velocity gradient, when the flow encountered the cylinder nose, the velocity became, zero and kinetic energy transformed into the potential energy. The downflow was generated subsequently. When the cylinder becomes inclined, the incoming flow velocity can be decomposed to normal ($V_n$) and tangential ($V_p$) components, whose magnitudes are all smaller than the velocity vector ($V$). For the upstream-inclined cylinder, in addition to the pressure gradient due to the converting velocity head $V_n$ into pressure head, a downflow formed by the $V_p$ due to the pressure gradient in the same direction of the downflow. This increased the strength of the downflow, resulting in the deeper scour hole. For the downstream-inclined cylinder, the $V_p$ was in the opposite direction of the downflow, and then weakened the strength of the downflow. This is the main reason for the decrease in the scour depth.

Besides the explanations above, it is noteworthy that the shape of the cross-section of the inclined cylinder is an ellipse, which is more streamlined than the circular. Previous studies [36] show that the more streamlined the project frontal area of the obstacle, the less momentum is transferred downward to the bed upstream of the obstacle. From this view, the downstream-inclined cylinder is more streamlined than the upstream-inclined cylinder, which leads to the weaker downflow for the downstream-inclined cylinder.

4.2. Flow Fields behind the Cylinder

The inclination and the submergence also change the flow fields behind the cylinder. From Figures 8 and 9, it can be seen that for the unsubmerged cylinder (Figures 8a and 9a), due to the high Reynolds number ($Re_d = UD/\nu = 2.5 \times 10^8$), the vortex shedding behind the cylinder was strong, increasing the flow turbulence and eroding the entrained sediment away from the back of the cylinder. For the submerged vertical cylinder (Figure 8b), a circulation region behind the cylinder emerged, as shown by the experiment results [13], due to the incoming flow passing through the top of the cylinder suppressing the vortex shedding from the cylinder. For the upstream-inclined cylinder (Figures 8c,d), when $\alpha = -15^\circ$ (Figure 8d), the streamlines behind the cylinder was similar to the vertical cylinder (Figure 8b); when $\alpha$ increased to $-30^\circ$ (Figure 8c), this phenomenon disappeared. When the cylinder was inclined to the downstream (Figure 7e,f), there was no circulation region
(Figure 8b) behind the cylinder. As the scour progressed, the flow fields behind the cylinder had no circulations behind the cylinder for all conditions (Figure 9), probably due to the changes of the morphology around the cylinder.

![Figure 9](image)

**Figure 9.** Streamlines and the contour of $V_z$ in symmetry plane at $t = 320$ s, (a–f) represents Case 1 to Case 6 in Table 2, respectively.

![Figure 10](image)

**Figure 10.** Schematic view of velocity in front of the inclined cylinder.

Figure 11 shows the contour of the $V_z$ and the streamlines at $x = 0.925$ m at the initial scour process. For the unsubmerged cylinder (Figure 11a), the streamlines behind the cylinder were asymmetric. Two vortices with contrary rotate directions can be recognized, indicating the violent alternate vortex shedding behind the cylinder. For the submerged cylinder, the distribution of the streamlines behind the cylinder is symmetrical, which means the alternate vortex shedding is suppressed by the submergence of the cylinder. For the upstream-inclined cylinder (Figure 11c,d), two pairs of vortices can be observed behind the cylinder when $\alpha = -30^\circ$ (Figure 11c). As the inclination angle decreased to $-15^\circ$ (Figure 11d), there was an additional pair of vortices near the bed surface, which is similar to the vertical one (Figure 11b). These additional vortices are the legs of the horseshoe vortex, which is similar to the prior results [13]. As the inclination angle increased, these
legs of the horseshoe vortex vanished, due to the weakened horseshoe vortex. The flow fields behind the downstream-inclined cylinder showed a difference with the upstream-inclined cylinder. For the smaller inclination angle (Figure 11e), the distribution of the streamlines was similar to the vertical cylinder (Figure 11b). There was only one pair of vortices near the bed. As the inclination angle increased (Figure 11f), these vortices moved up.

**Figure 11.** The contour of the $V_z$ and the streamlines behind the cylinder at $x = 0.925 m$ at $t = 0 s$, (a–f) represents Case 1 to Case 6 in Table 2, respectively.

4.3. Vorticity Distribution in front of the Cylinder

Figure 12 illustrates the vorticity distribution in front of the submerged cylinder in the $y$-direction ($\omega_y = \partial V_z / \partial z - \partial V_y / \partial x$) in the symmetry plane at $t = 0 s$. The horseshoe vortex was located in the maximum value of the vorticity. The position and the intensity of the horseshoe vortex were both influenced by the inclination of the submerged cylinder. For the upstream-inclined cylinder, the intensity of the horseshoe vortex decreased with the inclination angle, while the distance between the horseshoe vortex and the cylinder increased with the inclination angle. However, the distribution of the vorticity of the downstream-inclined cylinder was different from the upstream-inclined cylinder. The horseshoe vortex moved to the upstream surface of the cylinder, and the distance between the
horseshoe vortex and the cylinder decreased with the inclination angle. The intensity of the horseshoe vortex was comparable with the vertical cylinder when the inclination angle was smaller (α = 15°), and as the inclination increased (α = 30°), the intensity decreased, showing the nonlinear relationships between the inclination angle and the intensity of the horseshoe vortex.

![Figure 12](image)

**Figure 12.** The distribution of the vorticity in front of the cylinder.

### 4.4. The Distribution of the Bed Shear Stress

The distribution of the bed shear stress around the cylinder is presented in Figure 13. The bed shear stress was influenced by the inclination direction and angle, and had a significant effect on the evolution of the morphology around the cylinder. The highest bed shear stress occurred in the unsubmerged case (Figure 13a), which is consistent with the previous studies [13,14]. The submergence reduced the bed shear stress. For the upstream-inclined cylinder (Figure 13c,d), the maximum bed shear stress moved to the upstream sides, compared with the vertical cylinder (Figure 13b). The location of the peak bed shear stress moved upstream with the increasing inclination angle. The peak bed shear stress of the upstream-inclined cylinder was larger than that of the vertical cylinder and increased with the inclination angle. When the cylinder inclined to the downstream, the location of the peak bed shear stress moved to the downstream side. When α = 30° (Figure 13f), the peak value of the shear stress was higher than that in the vertical one (Figure 13b), which may be attributed to the accelerated flow at the sides of the cylinder.

### 4.5. The Morphology around the Cylinder

The bed morphology around the cylinder at an equilibrium situation is shown in Figure 14. The submerged cylinder (Figure 14b) experienced a minor scour compared with the unsubmerged cylinder (Figure 14a), which agrees with the prior experiments [14–16], indicating that the submergence leads to the decrease in the scour depth around the cylinder. The inclination changes the location of the scour hole. When the cylinder inclined to the upstream (Figure 14c,d), though the strength of the horseshoe vortex was weaker than that of the vertical cylinder (Figure 12), the bed surface in front of the cylinder was more vulnerable to erosion due to the stronger downflow (Figures 8 and 9). The bed in front of the cylinder experienced a more violent scour towards which the maximum scour depth moved, which is also consistent with the shear stress distribution shown in Figure 13.
Figure 13. The distribution of the bed shear stress, (a–f) represents Case 1 to Case 6 in Table 2, respectively.

Figure 14. Bed morphology around the cylinder at $t = 400$ s, (a–f) represents Case 1 to Case 6 in Table 2, respectively.

For the downstream inclined cylinder, the decrease in the scour depth in front of the cylinder can be attributed to the weakened downflow. Through the intensity of the horseshoe vortex was comparable with the vertical cylinder (Figure 12), the downflow in front of the cylinder was greatly weakened compared with the vertical cylinder (Figures 8b and 9b) and the upstream-inclined cylinder (Figures 8c,d and 9c,d). The strength of the downflow decreased with the inclination angle,
reducing the erosion rate in front of the cylinder. The scour hole on the sides of the cylinder became more obvious, and the maximum scour depth was located in this area, which is consistent with the distribution of the shear stress (Figure 13). When the cylinder inclined to the downstream, its shape of the cross-section was more hydrodynamic [37], leading to a higher velocity at the side of the cylinder and causing obvious scour in this area.

Figure 15 shows the comparison of the maximum scour depth around the submerged cylinder with different inclined conditions. For the downstream-inclined cylinder, the maximum scour depth monotonically decreased with the inclination angle, which is consistent with the prior unsubmerged experiments [22]. However, when the cylinder inclined to the upstream, the maximum scour depth did not increase monotonically with the inclination angle. For the larger inclination angle \( \alpha = -30^\circ \), the maximum scour depth was smaller than the case with a smaller inclination angle \( \alpha = -15^\circ \).

The local scour is attributed to the interaction of the downflow and the horseshoe vortex. For the downstream-inclined cylinder, the intensity of the horseshoe vortex varied slightly with the increased inclination, while the strength of the downflow obviously decreased, which eventually resulted in the monotonical variation of the maximum scour depth. When the cylinder inclined to the upstream, the intensity of the horseshoe vortex decreased with the inclination angle. The strength of the downflow increased with the inclination angle, which caused the nonmonotonic maximum scour depth for the upstream-inclined cylinder. There may be a compromised inclination angle for the downflow and the horseshoe vortex of the upstream-inclined cylinder, which will lead to the most violent local around the cylinder.

![Figure 15. Maximum scour depth around the submerged cylinder with different inclination angles.](image)

4.6. Research Limitation and Future Interest

In this paper, we present the inclination effect on the flow fields and the local scour around the submerged cylinder. Although the variation of the flow fields and the morphology were obtained and discussed above, there are still some limitations here. Firstly, only the steady flow condition is considered here; however, in the coastal and ocean environment, the unsteady flow conditions such as the waves or tides are dominated, so our future interest will focus on this unsteady condition. Secondly, some discrepancies exist in the validation of the hydrodynamic model in Section 3.1, particularly in the area which is closed to the cylinder and the bed surface, this deviation may be attributed to the turbulence model, which is needed in the further research.
5. Conclusions

A numerical model based on the RANS equations along with the RNG turbulent model and a sediment transport model was established to study the inclination effect on the flow fields and the local scour around a submerged cylinder. The modeled velocity distribution and the scour depth evolution are coincident with existing experimental measurements as well as numerical results of Roulund et al. [2] and Khosronejad et al. [12]. The main findings are summarized as follows.

(1) The strength of the downflow in front of the cylinder changes monotonically with the inclination angle \( \alpha \). When the cylinder inclines to the upstream, the strength of the downflow increases with the inclination angle. In cases of downstream inclination, the strength of the downflow decreases with the inclination angle.

(2) The inclination changes the position and the strength of the horseshoe vortex. For the upstream-inclined cylinder, the strength of the horseshoe vortex in front of the cylinder is suppressed, while the distance between the horseshoe vortex and the cylinder increases in comparison with the vertical case. When the cylinder inclines towards downstream, the horseshoe vortex gets closer to the cylinder, while the vortex strength depends on the inclination angle. For a small inclination angle (\( \alpha = 15^\circ \)), the strength of the horseshoe vortex slightly increases compared with the vertical case. When the inclination angle increases to \( 30^\circ \), the strength of the horseshoe vortex decreases compared with the vertical case.

(3) The local scour around a submerged inclined cylinder is dominated by the interaction of the downflow and the horseshoe vortex. The maximum scour depth decreases with the inclination angle for the downstream-inclined cylinder, while for the upstream-inclined cylinder, the scour depth does not vary monotonically with the inclination angle.

(4) The inclination of the cylinder also changes the morphology of the scour hole. When the cylinder inclines to the upstream, a more violent erosion takes place in front of the cylinder so that the scour hole moves to the upstream. For the downstream-inclined cylinder, the scour depth in front of the cylinder decreases, while the scour on the sides of the cylinder becomes more obvious. For the upstream-inclined cylinder, the stronger downflow makes the bed surface in front of the cylinder more vulnerable to erosion, and the accelerated flow at the sides of the cylinder causes obvious scour on both sides of the cylinder for the downstream cases.

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