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CURRENT-INDUCED SEABED SCOUR AROUND A PILE-SUPPORTED HORIZONTAL-AXIS TIDAL STREAM TURBINE

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Key words: tidal stream energy, sediment scour, numerical model, fluid-structure interaction.

ABSTRACT

Tidal stream energy has attracted more and more attentions of researchers and engineers of coastal studies in recent years, as it is renewable, predictable and environmentally friendly. Although many efforts have been made for the application of tidal stream energy, the scouring process in the vicinity of a pile-supported tidal stream turbine remains unclear. This study develops a mathematical model, consisting of hydrodynamic module, General Moving Object (GMO) module and sediment scour module, to numerically investigate the fluid-structure interaction and its induced sediment scour process around such a combined structure. Only a steady current is considered in the model, and the numerical model is verified by comparing with the well-documented physical experiments. The flow becomes extremely complicated after interacting strongly with the blades of tidal stream turbine, and a large area with low-velocity is formed behind the structures. The scouring process is very strong in the early stage, and it takes place with an asymmetrical pattern behind the pile foundation. Lower installation elevation of turbine leads to a stronger scour, while a stronger incoming velocity results in a wider area of seabed scour.

I. INTRODUCTION

There is an increasing demand for energy globally in recent decades, and many efforts have been devoted to the development of alternative renewable energies. Tidal stream energy is one of the promising marine renewable energies, and it gains more and more attentions nowadays. The main advantages of tidal stream energy are reliable, vast, predictable, less influenced on offshore environment, easily constructed, low cost and more profitable (Batten et al., 2008; Khan et al., 2009). Many types of tidal stream turbine are developed for extracting horizontal tidal kinetic energy (such as SeaGen), and the pile-supported horizontal-axis tidal stream turbine is one of the most popular turbines (Haydar et al., 2012). It is well-known that the flow motion around a pile foundation can be very complex and may lead to scouring phenomenon. The moving blades of a turbine may largely change the scour pattern and further increase scour depth around the pile foundation. An unexpected seabed scour may cause failure of a pile foundation, which should be carefully checked for the design of tidal stream turbine.

The performance of tidal stream turbine and its surrounding flow motion have been widely studied by field observation, experimental measurement and numerical simulation. For example, the famous offshore full-scale turbine, SeaGen, was installed and monitored in Northern Ireland's Strangford Lough in 2008 and it made a significant contribution to the success of the world's first commercial-scale tidal stream turbine. Although field test provides truly representative data, it is very expensive and almost impossible to control the sea state. To overcome these shortages, many laboratory experiments have been carried out, although laboratory model may not truly mimic the real complex offshore conditions (Myers et al., 2011; Myers and Bahaj, 2012). A recent experimental study of Tedds et al. (2014) investigated the near-wake of a model of horizontal-axis tidal stream turbine device in a large-scale re-circulating water channel facility, providing the most complete three-dimensional velocities and Reynolds stress data. Numerical models solving Navier-Stokes equations have also become popular as they are generally accurate, time-saving and cost effective. Nowadays, many models are developed for turbine design (Egarr et al., 2004; Goundar and Ahmed, 2013),

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hydrodynamic performance (O'Doherty et al., 2009) and vortexes in wake region (Macleod et al., 2002; Seokkoo et al., 2012).

Seabed scour in the vicinity of supporting piles is likely to cause structural instability, and is mainly governed by fluid flow, geometry of foundation and seabed conditions (Rambabu et al., 2003). The development of seabed scour around pile structures has been widely studied by field measurements (Whitehouse et al., 2011), laboratory experiments (Sumer et al., 2001; Sumer, 2007) and numerical simulations (Nielsen et al., 2013; Ehteram and Mahdavi, 2014), and these research results well serve scour protection for the foundation of offshore wind farm in recent years. It is found that turbine rotors change the boundary layer profile, and consequently alter the formation of horseshoe vortex and seabed scour process around the structures (Chen and Lam, 2014a). To date, there is no field measurement of seabed scour around a pile-supported horizontal-axis tidal stream turbine. The research work on such kind of scour topic is very limited. Chen and Lam (2014b) proposed the potential equations for the prediction of scour around a tidal stream turbine and recommended the consideration of the rotor into the existing equations for future research. However, the details about the current-induced seabed scour around the mono-pile foundation of a tidal stream turbine are still unavailable.

This study is to numerically investigate the current-induced seabed scour around a pile-supported horizontal-axis tidal stream turbine. A numerical model based on FLOW-3D package is applied for this complex fluid-seabed-structure interaction problem, and it is validated by the well-documented laboratory experiments. This model is further used to study the effects of installation elevation of a tidal stream turbine and inlet velocity on the seabed scour, aiming to achieve a better understanding of seabed scour around the mono-pile foundation of a tidal stream turbine.

II. MODEL DESCRIPTION

In this study, a commercial computational fluid dynamics (CFD) code, FLOW-3D package, is adopted to simulate the hydrodynamics and sediment transportation around a pile-supported horizontal-axis tidal stream turbine. The mathematical model consists of hydrodynamic module, General Moving Object (GMO) module and sediment scour module.

1. Hydrodynamic Module

In hydrodynamic module, the Reynolds-Averaged Navier-Stokes equations are solved. The VOF (Volume of Fluid) method is used to track free water surface, and the RNG k-ε turbulence model is chosen to simulate turbulence transport. The equation of mass conservation for fluid flow can be written as below:

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + \frac{\partial}{\partial y}(\rho u A_y) + \frac{\partial}{\partial z}(\rho u A_z) = R_{DIF} + R_{SOR} \quad (1)$$

where V_F is the fractional volume open to flow, ρ is the fluid density, R_{DIF} is a turbulent diffusion term, and R_{SOR} is a mass source. The velocity components (u, v, w) are in the coordinate directions (x, y, z). A_x is the fractional area open to flow in the x-direction, and A_y and A_z are similar area fractions for flow in the y and z directions, respectively.

The equations of momentum conservation are given below:

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}uA_x\frac{\partial u}{\partial x} + vA_y\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_x + f_x - b_x - \frac{R_{SOR}}{\rho V_F}(u - u_w - \delta u_s) \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F}uA_x\frac{\partial v}{\partial x} + vA_y\frac{\partial v}{\partial y} + wA_z\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + G_y + f_y - b_y - \frac{R_{SOR}}{\rho V_F}(v - v_w - \delta v_s) \quad (3)$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_F}uA_x\frac{\partial w}{\partial x} + vA_y\frac{\partial w}{\partial y} + wA_z\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + G_z + f_z - b_z - \frac{R_{SOR}}{\rho V_F}(w - w_w - \delta w_s) \quad (4)$$

in which (G_x, G_y, G_z) are body accelerations, (f_x, f_y, f_z) are viscous accelerations, (b_x, b_y, b_z) are flow losses in porous media or across porous baffle plates, and the final terms account for the injection of mass at a source represented by a geometry component. The term $U_w = (u_w, v_w, w_w)$ is the velocity of the source component, which will generally be non-zero for a mass source at a GMO. The term $U_s = (u_s, v_s, w_s)$ is the velocity of the fluid at surface of the source relative to the source itself. When $\delta = 0.0$, the source is of the stagnation pressure type. If $\delta = 1.0$, the source is of the static pressure type. At a stagnation pressure source, fluid is assumed to enter the domain at zero velocity. Therefore, pressure must build up at the source to move the fluid away from the source. At a static pressure source the fluid velocity is computed from the mass flow rate and the surface area of the source. In this case, no extra pressure is required to propel the fluid away from the source.

2. GMO Module

GMO module is applied to calculate fluid-structure interaction in FLOW-3D package. The core of GMO is FAVOR (Fractional Area/Volume Obstacle Representation) method, which is used to describe the characteristics and motions of a rotational tidal stream turbine.

$$\frac{\partial}{\partial t}(\rho V_F) + \nabla \cdot (\rho u A) = S_m \quad (5)$$

in which S_m is a physical mass source term of fluid. A is the area fraction changing with time in moving object problems, and its impacts on fluid flow must be considered in the case of a tidal stream turbine.

3. Sediment Scour Module

Suspended and packed sediments are considered in the sediment scour module. Suspended sediment is transported by advection along with the fluid, and the transport equation for each sediment species i is

$$\frac{\partial c_{s,i}}{\partial t} + \nabla \cdot (\overline{u} c_{s,i}) = 0 \tag{6}$$

where $c_{s,i}$ is the concentration of suspended sediment, in unit of mass per unit volume and $\overline{u}$ is the mean velocity of the fluid/sediment mixture. The momentum balances for each sediment species and the fluid-sediment mixture can be given as

$$\frac{\partial c_{s,i}}{\partial t} + \overline{u} \cdot \nabla u_{s,i} = -\frac{1}{\rho_{s,i}} \nabla P + F - \frac{K_i}{f_{s,i} \rho_{s,i}} u_{r,i} \tag{7}$$

$$\frac{\partial u}{\partial t} + \overline{u} \cdot \nabla u = -\frac{1}{\rho} \nabla P + F \tag{8}$$

where $u_{s,i}$ is the velocity of sediment species, ρ is the density of sediment material, $f_{s,i}$ is the volume fraction of sediment species, P is the pressure, K is the drag function, F includes body and viscous forces, and $u_{r,i}$ is the relative velocity.

For the bed-load transport (whereby the sediment particles roll or bounce along the bottom), the model used in this study is from Meyer, Peter and Muller (Soulsby, 1997). The equation predicting the volumetric flow of sediment per unit width over the surface of the packed bed is

$$\Phi_i = \beta_i (\theta_i - \theta''_{cr,i})^{1.5} \tag{9}$$

where θ_i is the local Shields number (a function of local shear stress), $\theta''_{cr,i}$ is the critical Shields parameter, and β_i is typically equal to 8.0 (Van Rijn, 1984). A higher value of Φ_i may lead to a stronger sediment transportation.

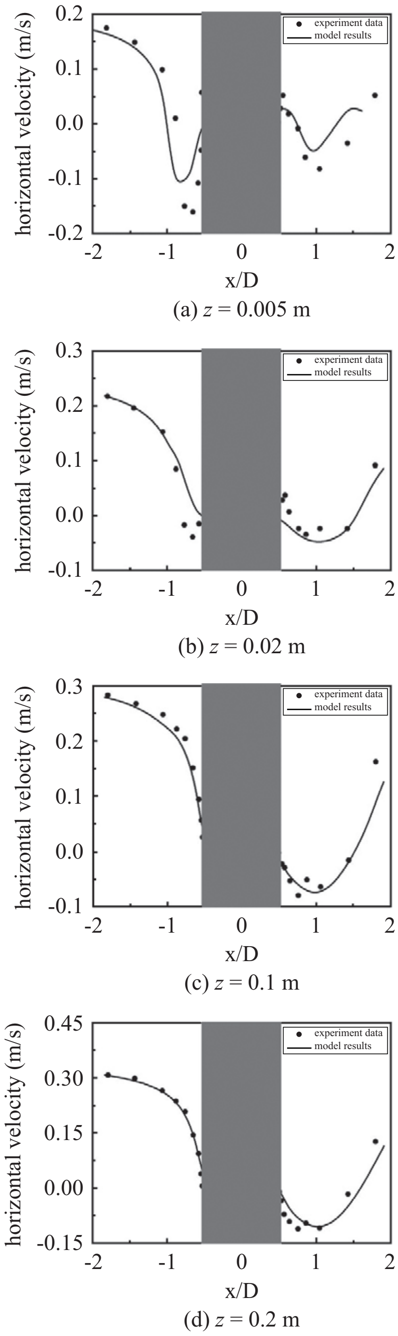


Fig. 1. Comparisons of horizontal velocities between simulation and experiment of Roulund et al. (2005).

III. RESULTS AND DISCUSSION

1. Model Validation

Before the mathematical model was applied for the investigation of seabed scour around a horizontal-axis tidal stream turbine with a supporting cylinder, the validation studies had been carried out and the numerical results had been compared with those experimental results of Roulund et al. (2005) and Zhao et al. (2010).

The experiment of Roulund et al. (2005) was conducted in a flume with 35 m long and 3 m wide. The vertical cylinder with a diameter of 0.536 m was fixed on a smooth flume bottom. Water depth was maintained at 0.54 m, and flow velocity of inlet was 0.326 m/s. Flow velocities were measured at upstream side and lee side of the vertical cylinder, at four different elevations $z = 0.005$ m, $z = 0.02$ m, $z = 0.1$ m and $z = 0.2$ m. Figs. 1 and 2 compare the simulated and measured flow velocity at each elevation, indicating a good agreement

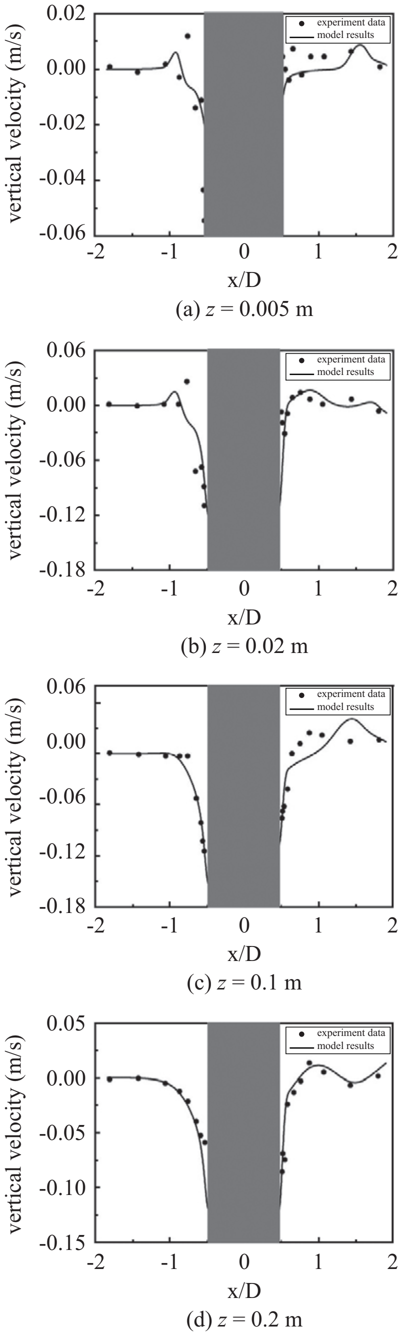


Fig. 2. Comparisons of vertical velocities between simulation and experiment of Roulund et al. (2005).

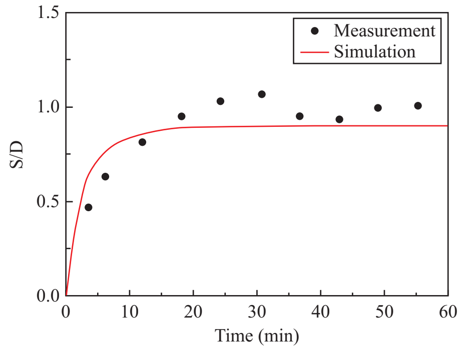


Fig. 3. Comparisons of simulated and measured scour depth in front of the mono-pile of Zhao et al. (2010).

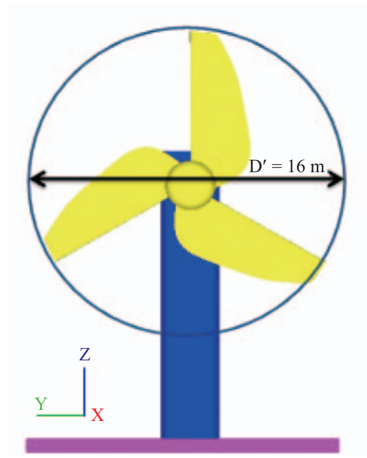


Fig. 4. Sketch of tidal stream turbine with a mono-pile foundation.

between numerical simulation and experimental result. The results show that this model has a great potential in predicting the complex flow structure around a cylinder.

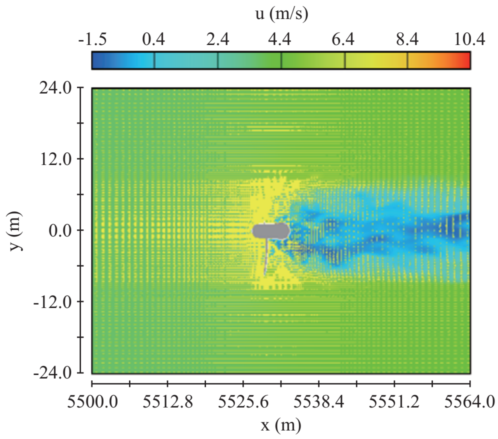
The mathematical model was also applied to numerically repeat the experimental results of Zhao et al. (2010). Experiments were conducted in a water flume of 4 m wide, 2.5 m deep and 45 m long. The flume was equipped with a pump of 1 m^3/s capacity. A concrete sand pit of 4 m long, 4 m wide and 0.25 m deep was built in the test section. Only the sand with a median particle size of d_{50} = 0.40 mm was used in experiments. Water depth in the test section was maintained at 0.5 m for all tests. Fig. 3 shows the comparison of the calculated scour depth development at the most front edge of the cylinder (with a diameter of 0.1 m) with the experimental data. A good agreement between simulation and measurement indicates that this mathematical model is suitable for the simulation of seabed scour process around a mono-pile foundation.

2. Example with Tidal Stream Turbine

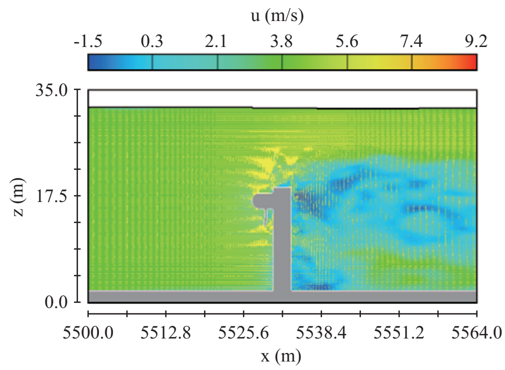
This numerical model is further used to study the velocity field and seabed scour around a horizontal-axis tidal stream turbine with a supporting cylinder. The numerical flume has a length of 200 m in x-direction, a width of 60 m in y-direction and a height of 33 m in z-direction. The horizontal-axis tidal stream turbine consists of 3 blades with 16 m in diameter (D′) and 0.4 m in thickness. The hub of turbine is 2.6 m in diameter and 3.56 m in length (Fig. 4). In this study, the supporting vertical cylinder is 17 m in height and 3 m in diameter. The blockage ratio (area of turbine/area of the y-z plane) is about 0.25, and the rotor resistance remains constant. The angle from leading edge to trailing edge of turbine is fixed as 70°, and incoming current velocity is taken as 3.7 m/s. Five different types of components of gravel are defined in Table 1,

Table 1. Properties of different types of gravel in seabed.

Class name (ID)	Minimum sediment size (mm)	Angle of repose (degree)	Critical Shields number (dimensionless)
Very coarse	32	40	0.050
Coarse	16	38	0.047
Medium	8	36	0.044
Fine	4	35	0.042
Very fine	2	33	0.039

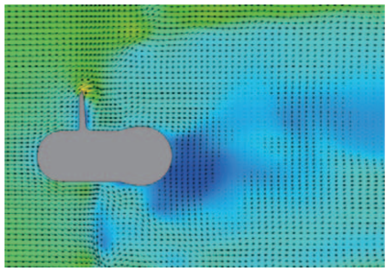


(a) x-y plane

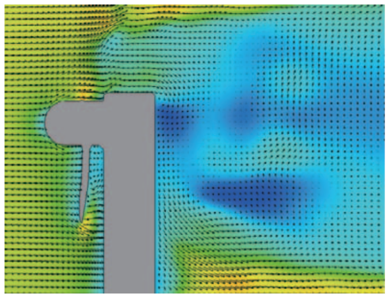


(b) x-z plane

Fig. 5. Instantaneous velocity field in the vicinity of the turbine and supporting cylinder.

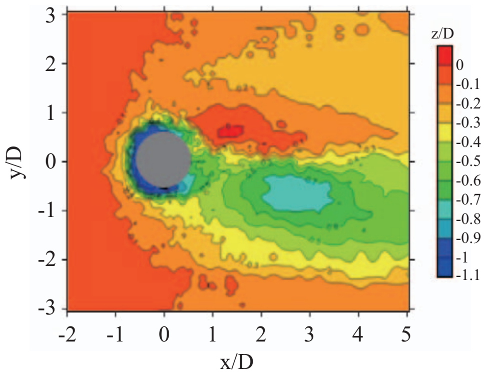


(a) x-y plane

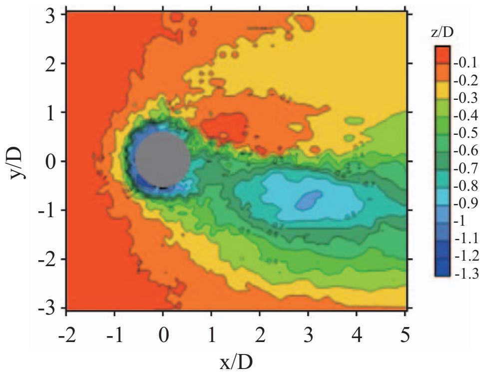


(b) x-z plane

Fig. 6. Zoom-in views of instantaneous velocity field in the vicinity of the turbine.



(a) $t = 5$ min



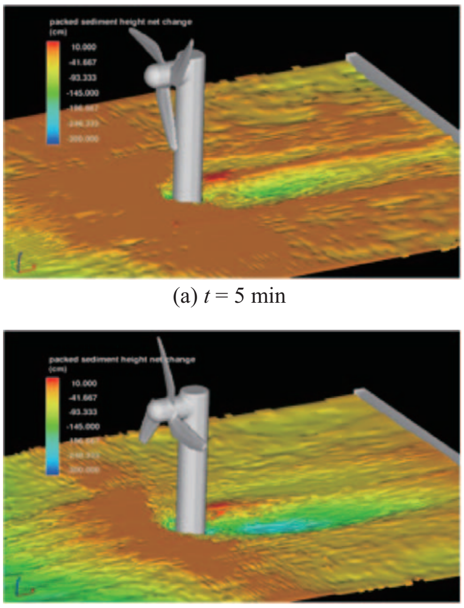
(b) $t = 30$ min

Fig. 7. 2D pattern of seabed scour around tidal stream turbine.

and each of them occupies 20% of the total volume of seabed.

Fig. 5 shows the instantaneous velocity field around the tidal stream turbine and its supporting mono-pile in x-y plane and x-z plane. It is found that a large area with low-velocity takes place behind the structure, due to the energy extraction by the turbine. Meanwhile, the stream velocity in cross section where the turbine is located is somehow increased as the structure partially blocks the passing space of flow. The negative value of current velocity indicates that flow vortex is formed after the current interacts with the blades of turbine (see also Fig. 6). It is noted that the low-velocity area is obviously larger than that in the case of a mono-pile foundation only.

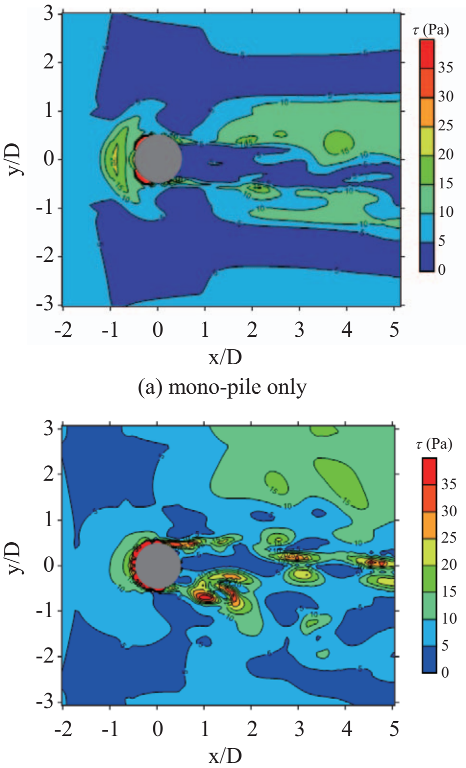
Figs. 7 and 8 show the scour patterns of seabed at time $t = 5$ min and $t = 30$ min in 2D and 3D views. It indicates that the current-induced scouring process is very strong in the early stage of sediment scour, and a deep hole can be quickly formed in the vicinity of pile foundation. The scour pattern is



(a) t = 5 min

(b) t = 30 min

Fig. 8. 3D pattern of seabed scour around tidal stream turbine.

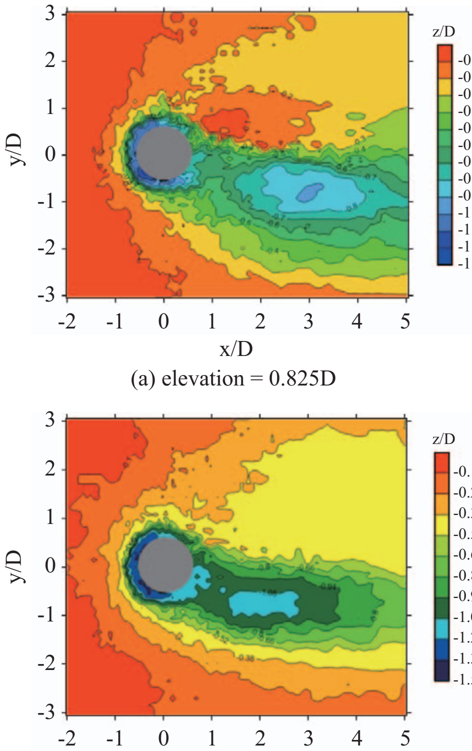


(a) mono-pile only

(b) mono-pile with turbine

Fig. 9. Distribution of shear stress at seabed surface.

obviously asymmetrical behind the pile foundation due to asymmetrical shear stress (Fig. 9), which is related to the rotating motion of turbine blades. When facing an incoming flow, the blades are rotating clock-wise in this case. A deeper hole by current-induced scouring can be identified.



(a) elevation = 0.825D

(b) elevation = 0.575D

Fig. 10. Influence of installation elevation of turbine on seabed scour around tidal stream turbine.

3. Parametric Study

Installation elevation of a turbine (distance between the seabed surface and hub center of a turbine) and incoming velocity of steady current are varied for the investigation of their impacts on hydrodynamics and current-induced seabed scour around such a combined structure.

Two different elevations, 13.2 m (0.825D) and 9.2 m (0.575D), are adopted in the model. The rotating speed of a turbine is about 1.35 rad/s with an installation elevation being 0.575D, and about 1.42 rad/s with an installation elevation being 0.825D. Increase of installation elevation also leads to a stronger fluctuation of water level above the turbine. Fig. 10 shows the patterns of seabed scour in the cases with different installation elevations at t = 30 min. The influence of installation elevation on seabed scour is obvious, and a lower elevation of installation results in a deeper scour around the structure. When the installation elevation of tidal stream turbine is lowered from 0.825D to 0.575D, the maximal depth of scour varies from 1.31 m to 1.50 m.

Incoming velocity, another key parameter significantly affect hydrodynamics and current-induced seabed scour, and is increased from 3.7 m/s to 4.8 m/s with a fixed installation elevation being 0.825D in the model. It is expected that an increasing incoming velocity increases kinetic energy that the turbine can extract. However, the increase of incoming

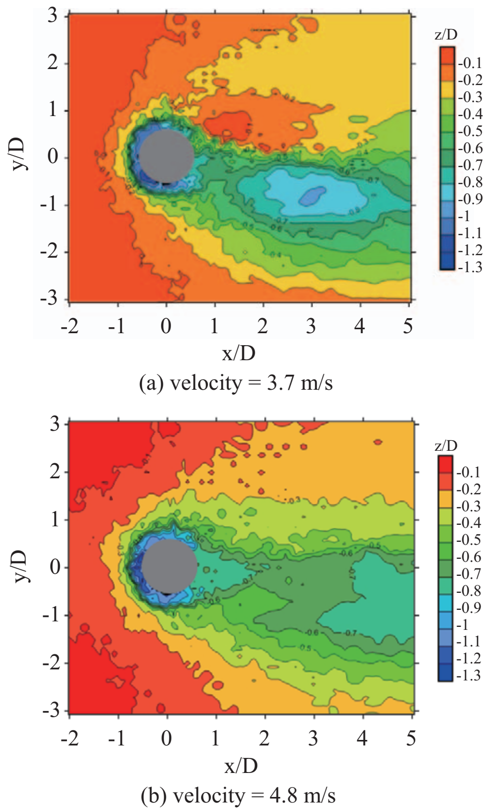


Fig. 11. Influence of incoming velocity on seabed scour around tidal stream turbine.

velocity will make the whole structure of turbine unstable, and the rocking motion of structure is likely to take place. Also, the fluctuation of free water elevation above the turbine becomes more violent (from 0.1 m to 0.3 m) when incoming velocity increases (from 3.7 m/s to 4.8 m/s). As shown in Fig. 11, a strong current in upstream side leads to a wider range of seabed scour and more sediment particles transported to the lee side of structure.

IV. CONCLUSIONS

This study numerically investigated the current-induced seabed scour around a pile-supported horizontal-axis tidal stream turbine. Based on these numerical simulations, the following conclusions are made. (1) The mathematical model developed in this study is suitable for the investigation of the complex hydrodynamics and scouring process in the vicinity of a tidal stream turbine. (2) The wake flow becomes extremely complicated after interacting with the blades of tide stream turbine, and a large area with low-velocity is formed behind the structure. The current-induced seabed scour around the turbine structure is asymmetric, which is different from that around a mono-pile foundation only. (3) Lower installation elevation of a turbine leads to a stronger seabed scour, while a stronger incoming velocity widens the area of seabed scour.

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