A Feasibility Study of Reducing Scour Around Monopile Foundation Using A Tidal Current Turbine

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Abstract

The monopile foundations of offshore wind turbines in shallow waters are susceptible to be affected by tidal scour, which takes away the sand and soil around the monopiles and poses a serious threat to the safety of the turbines. To mitigate this issue, much effort has been made previously. However, all of the existing protective measures do not have added value other than scouring mitigation. In view of this, a new scour mitigation measure that utilizes tidal current turbine (TCT) is investigated in this study, which can not only reduce the scour around the wind turbine foundation but can also generate clean power simultaneously. In the research, the proposed method is studied by using a combined numerical simulation and laboratory testing approach. Both numerical calculation and experimental results have shown that a TCT installed in front of the monopile foundation of an offshore wind turbine does have a positive role in reducing the scour around the foundation when it generates electricity in the meantime. Moreover, the contribution of the TCT to scour reduction can be further improved through optimizing its installation position in front of the wind turbine.

Keywords: Scour; offshore wind turbine; fixed foundation; tidal current turbine

1. Introduction

The offshore wind industry has experienced rapid growth worldwide in recent years [1]. Recent statistics have shown that 409 offshore wind turbines were newly connected to the European grid in 2018, bringing the European offshore wind power installed capacity to 2,649 MW [2]. It is predicted that by 2020, the electricity generated from various renewable energy sources may account for 35% of the total electricity required by the UK [3]. These predictions have recently become more realistic as more studies have been tried to achieve such an ambitious target with the successful development of multiple super-large offshore wind turbines (OWTs), such as the 10 MW SeaTitan designed by the American energy technology company AMSC, the 10 MW ST10 designed and developed by Norwegian technology company Sway, the V164-8.0 MW OWT developed by Vestas, Haliade-X 12 MW OWT developed by GE, and so on [3]. The successful development of these offshore giants will certainly reduce the average cost of offshore wind power and make it more competitive in price than traditional fossil fuels [4].

The foundation of OWTs is not only expensive (about 35% of the total cost according to [5]) but also critical to the safety of OWTs. So far, although there have been multiple types of foundations applied to the OWTs such as monopile, gravity-based structure, jackets, and tripods, the majority of existing OWTs are still supported by monopile foundations [2] due to its mature technology as compared to other types of foundations. However, the reliability of monopiles is prone to be affected by tidal current particularly in shallow water [6]. When tidal current passes through the monopile, down-flows will be formed in front of the monopile, and vortices will be formed at both sides and in the wake region of the monopile [7]. They will stir and take away the sand and soil on the surface of the seabed around the monopile and create scour pits after a long term of scouring. The presence of these scour pits poses a serious threat to the safety of the turbines. The research has shown that when the scour depth reaches 1 pile diameter the head displacement of the pile may increase by 37% [8].

Scour was first observed in bridge engineering and since then much effort has been made to address this issue [9]. To date, a variety of scouring mitigation measures have been developed.

For example, sacrificial embankments [10,11], guide panels [7,12,13], collars [14,15], and pier slots [14] were used to reduce the intensity of the flowing water and weaken the strength of down-flows and horseshoe vortices; ripraps [16–20] and gabions [21] were used to enable scour reduction by providing a physical barrier [22]. All these measures have been shown effective in reducing the scour around bridge piles, however, not all of these measures are applicable to reduce the scour around the monopile foundation of OWTs. For example, it is known that riprap protection technology is difficult to apply in the river. The application of it in a harsh marine environment will become more difficult. The sacrificial embankment, guide panels, and collar technologies are only applicable to the river environment, where the direction of water flow is usually constant over time. However, they are not applicable to OWTs as the direction of tidal current may change from time to time. Finally, pier slot technology is also inapplicable to OWTs because opening a hole on the monopile foundation of an OWT may challenge the safety of the OWT.

The scour issue on the monopile foundation of an OWT was first discovered at the Egmond aan Zee wind farm in the Netherlands in 2010 [23]. In order to reduce the scour effect on OWTs, the effort was also made by scholars in recent years. For example, besides the traditional riprap protection technology that has already been applied to bridge piers, a countermeasure device was proposed in [4] to mitigate the scour by guiding the current flow around the monopile foundation. However, all these methods are passive technologies, they do not have any more added value except scour mitigation. In view of this, a new scour mitigation measure that utilizes tidal current turbine (TCT) is investigated in this study, which can not only reduce the scour around the wind turbine foundation but can also generate clean power simultaneously. In the research, the proposed technique will be numerically studied first in ANSYS Fluent and then experimentally verified in the tidal current tank in the laboratory.

2. Fundamental mechanism of the new countermeasure

As mentioned earlier, when the tidal current reaches the monopile of an OWT downflow is formed in front of the monopile, which will accelerate the current flow on both sides of the monopile [24]. Then, horseshoe vortices and annular acceleration current flow will occur on

both sides of the monopile as the down-flows touches seabed. The horseshoe vortices erode the seabed constantly, stirring and taking away the sand and soil on the seabed around the monopile foundations. In addition, pairs of counter-rotating vortices will also occur behind the monopile, which can take away suspended sand and soil from the seabed and finally produce a symmetrical scour pit behind the monopile. It has no doubt that the faster the tidal current speed, the stronger the intensity of the vortices will be. A schematic diagram of scouring around a monopile is shown in Fig.1. Consequently, the scour pits will occur sooner around the monopile foundation. Inspired by such an operating mechanism of scour, it can be speculated that the scour can be mitigated if the kinetic energy of the tidal current can be reduced before the tidal current reaches the OWT. The TCT is an ideal tool for such a purpose. When a TCT is operating in front of the monopile, its rotor will absorb kinetic energy from tidal current to generate electricity, thereby reducing the kinetic energy of tidal current in front of the OWT and defer the production of scour pit as a consequence. So, it can be said that, in principle, the TCT can help mitigate scour if it is deployed in front of an OWT.

Fig.1 Schematic diagram of the scour around a monopile foundation.

It is well known that the power generation efficiency of a TCT is highly dependent on the yaw angle [25]. In other words, the TCT works effectively only when its rotor plane is rightly facing the direction of tidal current. However, in real life the direction of tidal current around the monopile foundation of an OWT is not constant. It may vary from time to time. In order to ensure that the TCT can work effectively all the time and avoid the scour effects due to propeller jet velocities [26][27] and the negative impact of TCT on reducing scour pit depths [28][29],

the TCT will be suspended from a rotating platform, which can rotate around the monopile foundation of the OWT to ensure that the rotor plane of the TCT always faces the direction of the tidal current. The schematic diagram of the proposed technique is shown in Fig.2.

Fig.2 Schematic diagram of the proposed technique. (a) side view, (b) front view.

As compared to traditional scour reduction technologies, the proposed TCT-based technology is environmentally friendly and can generate clean electric power while mitigating the effect of scouring.

3. Setup of numerical model

In order to investigate the potential effectiveness of the proposed ideal on scour mitigation, a numerical study is conducted first with the aid of software ANSYS Fluent 18.0. The geometrical dimensions, meshing, numerical model, and boundary conditions used in the numerical calculations are briefly summarized below. Herein, the numerical study is implemented by two steps. In the first step, the feasibility of using TCT as a scour-countermeasure device is investigated from the perspectives of the streamline, eddy viscosity, and shear stress on the nearby seabed; in the second step, the scour mitigation effect of the TCT is investigated for different position of TCT in order to identify the best position of the TCT in front of the monopile foundation.

In the numerical research, to enable the comparison with the experimental results, the monopile and TCT are assumed placed in 1 m depth water. Considering in real life the tidal current speed reaches the maximum on the water surface and then decreases gradually with the increase of the distance away from the water surface and finally drops down to zero on the surface of the seabed. In order to understand the speed profile of the water flow in the tank, the flow speeds at different underwater distances were measured. The raw data measurement results and the corresponding data fitting curve are shown in Fig.3. The data fitting curve can be mathematically expressed as

$$U(z) = 0.259 \times z / (0.03564 + z) \quad (0 \leq z \leq 1 \text{ m}) \quad (1)$$

where z indicates the height above the seabed.

Fig. 3. Speed profile of tidal current.

From (1), it can be readily known that the water depth average speed is 0.22 m/s and the maximum current speed is 0.248 m/s.

In the numerical study, the outer diameter of the monopile foundation is 10 cm, its wall thickness is 1 cm. A three-bladed TCT is suspended from a platform attached to the monopile, as indicated in Fig.2. The rotor blades of the TCT are 17.5 cm long. They are placed on the hub of the rotor with a fixed pitch angle. As shown in Fig.4, the fluid domain considered in the numerical calculation is 1.8 m long, 1 m wide, and 1 m thick. The monopile foundation is placed in the center of the fluid domain. The center of its bottom surface is defined as the origin of the coordinate system, and the positive direction of the X-axis is the same as the direction of the

current flow. Such an arrangement not only leaves enough wake area behind the monopile foundation but also provides sufficient free space for the TCT.

Fig. 4. Fluid domain and the numerical models

Scouring can occur where there is excessive shear on the seabed surface [4], the maximum shear stress on the seabed surface is used as an indicator to assess the depth of scour pits. Due to that, the number of elements has an important effect on the calculation results. It is necessary to investigate the effects of the number of elements on the maximum shear stress on the seabed surface for obtaining the proper number of elements to accurately simulate the flow. Seven various numbers of elements were used to calculate the maximum shear stress on the seabed surface, the calculations are shown in Figure 5.

Fig. 5. The maximum shear stress versus the numbers of the meshes.

From Fig.5, it is found that the maximum shear stress shows a generally decreasing tendency with the increase of the number of mesh elements and finally reaches an asymptotic

value (i.e. 0.281 Pa) when the number of meshes reaches 9.45×10^6 . So, it can be said that a reliable assessment of the maximum shear stress can be obtained when the number of meshes is set to be 9.45×10^6 .

When setting the number of meshes to be 9.45×10^6 , the fluid domain in Fig.4 is meshed and the meshing results are shown in Fig.6. In order to accurately describe the flow behaviour around the monopile foundation and its influence on scouring while not causing excessive calculations, fine meshes are only adopted to discretize the fluid domain in the vicinity of the monopile foundation. The region being discretized using fine meshes is 0.3 m wide. The fluid domain in other regions is discretized using coarse meshes.

Fig. 6. An example of the meshing results. (a) side view, (b) top view.

Subsequently, a $k-\omega$ SST turbulence model is adopted for implementing the simulation calculations. Herein, it is worth noting that the $k-\varepsilon$ and $k-\omega$ models are two popular turbulence models. The former can better simulate the turbulent flow that is fully developed away from the wall surface, while the latter is more widely applied to solving boundary layer problems under various pressure gradients. However, both of them have problems in describing the turbulent flow in a real turbulent environment. In addition, they may show unsatisfactory performance in flows with high anisotropy, significant streamline curvature, flow separation, flows with recirculation region, or in flows that are affected by average rotation effect [30]. The $k-\omega$ SST turbulence model takes the advantages of both $k-\varepsilon$ and $k-\omega$ models [31], i.e. the $k-\omega$ SST

turbulence model retains the advantages of the original k - ω model on simulating the turbulent flow near the wall and the advantages of the original k - ε model on simulating the turbulent flow away from the wall. The eddy viscosity coefficient, k equation, and ω equation of the k - ε model can be calculated by using the following equations [32]:

Kinematic eddy viscosity

$$\nu_T = \frac{a_1 k}{\max(a_1 \omega, S F_2)} \quad (2)$$

Where the a_1 is parameters $a_1=0.31$, k is turbulence kinetic energy, ω is turbulence frequency, S is the invariant measure of the strain rate, the blending function F_2 is

$$F_2 = \tanh \left[\left[\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right) \right]^2 \right] \quad (3)$$

Where the h is water depth, β^* is parameters $\beta^*=0.09$, y is the distance to the nearest wall, ν is kinematic viscosity, the Turbulent kinetic energy is

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_j k) = P_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_j} \left[\left(\mu + \sigma_k \mu_T \right) \frac{\partial k}{\partial x_j} \right] \quad (4)$$

P_k is a production limit used in the turbulence equation to avoid the build-up of the turbulent kinetic energy in the stagnation region. U is velocity, i, j is indices for the scalar components of vectors, μ is viscosity, μ_T is turbulent viscosity, parameters $\sigma_{k1}=0.85$, $\sigma_{k2}=1$. P_k can be mathematically expressed as

$$P_k = \min \left(\mu_T \frac{\partial U_i}{\partial x_j} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right), 10 \beta^* \rho k \omega \right) \quad (5)$$

Where the ρ is water density, the specific dissipation rate is

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_j \omega) = \alpha \rho S^2 - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[\left(\mu + \sigma_\omega \mu_T \right) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (6)$$

Parameters $\sigma_{\omega 1}=0.5$, $\alpha_1=5/9$, $\alpha_2=0.44$, $\sigma_{\omega 2}=0.856$. The blending function F_1 is

$$F_1 = \tanh \left\{ \left\{ \min \left[\max \left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right), \frac{4\sigma_{\omega 2} k}{CD_{k\omega} y^2} \right] \right\}^4 \right\} \quad (7)$$

Where the $CD_{k\omega}$ is

$$CD_{k\omega} = \max \left(2\rho\sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, 10^{-10} \right) \quad (8)$$

The turbulence intensity 5% and hydraulic diameter 0.1 were used throughout the numerical simulation. The settings of the corresponding boundary conditions are shown in Fig. 7.

Fig. 7. The numerical model with boundary conditions.

4. Simulation results and discussions

4.1. Investigation of effectiveness

In order to highlight the positive contribution of the TCT to scour mitigation, the seabed scour around the monopile foundation before and after using the TCT is investigated in this section. The corresponding streamlines of the flow around the monopile are shown in Figure 8.

Fig.8. Streamlines after using the fishnet: (a) before using the TCT; (b) after using the TCT.

From Figure 8(a), it can be seen that the flow is disturbed when it reaches the monopile. Downflow is present in front of the monopile, vortices are present around the monopile, and pairs of counter-rotating vortices are present behind the monopile. From Figure 8(b), it is seen that in the presence of the TCT, the streamlines of the flow behind the TCT was significantly disturbed, i.e. not only the downflow but also the vortices around the monopile are affected. These streamlines may indicate the motions of the sand particles when they are stirred up by the vortices, but they cannot indicate the scouring effect directly. For this reason, the shear stress on the seabed is investigated. Since the shear stress on the seabed can indicate the strength of scouring, its distributions before and after using the TCT are calculated. In the scenario of using the TCT, the TCT was placed at 30 cm in front of the monopile and 10 cm above the seabed. The TCT rotates at its rated speed of 10 rev/min. The calculation results of the shear stress distributions obtained in the two scenarios are shown in Fig.9.

Fig.9. Shear stress distribution: (a) before using the TCT; (b) after using the TCT.

From Fig. 9, it is seen that, in both scenarios, the maximum shear stress occurs on both

sides of the monopile foundation, which suggests that the scour of the monopile foundation is more susceptible to occur first on both sides of the monopile foundation. The comparison of the results in Figs.9(a) and 9(b) has shown that, after using the TCT, the shear stresses on both sides of monopile are somewhat decreased. The maximum shear stress on the surface of the seabed is only 0.281 Pa, which represents a reduction of the maximum shear stress by approximately 8%. Apparently, the TCT does work in mitigating the scour around the monopile foundation of the OWT.

4.2. Investigation of the optimal installation position

It has no doubt that the TCT will have different effects on mitigating the seabed scour when it is placed at different positions in front of the monopile foundation of the OWT. Therefore, to maximise the contribution of the TCT to scour reduction, further research is conducted below in order to identify an optimal installation position of the TCT. In the research, the installation position of the TCT is determined by distance L in front of the monopile foundation and height H above the seabed, see Fig.2. To simplify the analysis, their influences on seabed scour will be investigated separately below. Firstly, the influence of distance L on seabed scour is investigated when the value of height H above the seabed is fixed. Their values in the investigated scenarios are listed in Table 1. In all of these scenarios, a constant rotational speed of the TCT was considered, it is 10 rev/min. The variation tendency of the maximum shear stress on the seabed surface against the distance L obtained in these scenarios is shown in Fig. 10. Where the maximum shear stress in the absence of the TCT was also calculated for comparison.

Table 1. Scenarios for investigating the influence of distance.

L (cm)	H (cm)
0, in the absence of the TCT	-----
10	10
20	10
30	10
40	10
50	10

Fig. 10. The calculated maximum shear stress versus the installation distance.

From Fig.10, it is found that the maximum shear stress on the seabed is 0.306 Pa in the absence of the TCT. After the TCT is used, the maximum shear stress shows a generally decreasing tendency first until it reaches the minimum value of 0.281 Pa when the distance L is 30 cm. Then, the maximum shear stress starts to increase gradually with the increase of the installation distance and reaches 0.307 Pa when $L = 50$ cm, which is very similar to the value of the maximum shear stress 0.306 Pa that is obtained in the scenario when the TCT is absent. Such a variation tendency of the maximum shear stress versus the installation distance suggests that:

- The installation distance of the TCT does affect its effect on mitigating the scour on the seabed around the monopile foundation of the OWT;
- The optimal installation distance of the TCT does exist and the maximum suppression of seabed scour can be obtained only at this optimal installation distance;
- As can be imagined, the TCT will have less influence on seabed scour when the TCT is placed farther than the optimal installation distance;
- The TCT does not effectively mitigate seabed scour either when it is placed too close to the monopile foundation. This phenomenon is different from our thinking. In order to understand the reason, the maps of eddy viscosity obtained respectively when the TCT is placed at distance 10 cm and the optimal distance 30 cm are shown in Fig.10.

Fig. 11. Maps of eddy viscosity obtained when the TCT is at different distances: (a) $L=10$ cm; (b) $L=30$ cm.

From Fig. 11, it is found that, as compared to the results shown in Fig.11(b) that are obtained when the TCT is placed at the optimal distance 30 cm, more downstream flow near the seabed in Fig.11(a) is indicated by red colour. This suggests that larger eddy viscosity is present in that region when the TCT is placed at 10 cm in front of the monopile foundation. The presence of larger eddy viscosity near seabed in Fig.11(a) may be because when the TCT is placed too close to the monopile foundation of the OWT, the turbulent flow generated by the rotor of the TCT cannot have a significant influence on the downflow and vortices around the monopile foundation, thereby failing to suppress seabed scour effectively.

Subsequently, the influence of the installation height of the TCT above the seabed on seabed scour is investigated. The installation distances L and heights H of the TCT considered in the investigated scenarios are listed in Table 2. The maximum shear stresses obtained in the scenarios characterized by different TCT installation height H are shown in Fig.12.

Table 2. Scenarios for investigating the influence of installation height.

L (cm)	H (cm)
0, in the absence of the TCT	-----
30	5
30	10
30	15
30	20
30	25

Fig.12. The calculated maximum shear stress versus the installation height.

From Fig. 12, it is found that the maximum shear stress in the absence of the TCT is 0.306 Pa. After the TCT is placed in front of the monopile foundation, the calculated values of the maximum shear stress become smaller, which indicates the positive role of the TCT in mitigating scour. Through further observing the variation tendency of the maximum shear stress against the TCT installation height, it is interestingly found that with the increase of the installation height from 5 to 25 cm, the maximum shear stress decreases first and reaches the minimum value of 0.281 Pa when $H = 10$ cm, then turns to increase and reaches 0.303 Pa when $H = 20$ cm. Such a variation tendency suggests that the installation height of the TCT also has a significant influence on its effect on seabed scour. When the TCT is placed too high or too low above the seabed, the seabed scour cannot be maximumly reduced. The seabed scour can be suppressed effectively only when the TCT is placed at an optimal height above the seabed. To ease understanding of this view, the maps of eddy viscosity obtained when the TCT is placed respectively at heights 5 cm and 10 cm are shown in Fig.13.

(a) (b)

Fig. 13. Eddy viscosities: (a) $H = 5$ cm, (b) $H = 10$ cm.

From Fig.13, it is found that compared to the downstream flow in Fig.13(b), more downstream flow near the seabed in Fig.13(a) is indicated by the red colour that represents larger eddy viscosity. This may be because when the TCT is placed too low above the seabed, the turbulent flow generated by its rotor can enhance the vortices on the seabed around the monopile foundation. There is no doubt that the enhanced vortices will cause more serious seabed scour.

5. Verification tests

Following the numerical study, experimental tests will be conducted in the laboratory in this section to understand the actual influence of a TCT on seabed scour around the monopile foundation of OWTs.

5.1. Setup of the experiments

All verification tests were conducted in a multifunctional tidal current tank. It is shown in Fig. 14. The tank is 14.65 m long, 5.9 m wide, and 1.8 m high. At both ends of the tank, the outer diameter is 5.9 m and the inner diameter is 2.4 m. The testing section is set in the middle of the front channel of the tank. A sand basin is designed on the ground surface of the testing section in order to simulate seabed. The sand basin is 3.8 m long, 1.35 m wide, and 0.3 m deep. The sand used for marking the artificial seabed in the basin is real river sand. After being screened and washed, the size of the sand particles varies from 0.1 to 0.5 mm, the median size (d_{50}) of the sand in the basin is 0.2 mm. To facilitate observation, a glass window is designed

on the front wall of the tank. The size of the window is 2.7×1.3 m. The water flow in the tank is driven by two axial pumps placed in the channel behind the tank. The rated power of the axial pumps is 10 kW and 15 kW, respectively. Therefore, the flow speed in the tank can be controlled by controlling the rotational speed of the marine propellers. It varies from 0.1 m/s to 2.0 m/s as needed. The monopile was placed in the center of the sedimentation basin, as shown in Fig. 15. The TCT is placed directly in front of the monopile.

Fig. 14. The tidal current tank used in laboratory tests: (a) Side view; (b) Front view.

Fig. 15. Schematic diagrams of the tidal current tank in both sectional and plan views.

In the laboratory tests, the scale model of the monopile foundation is emulated by a 2 m long plexiglass pipe. The outer diameter of the pipe is 0.1 m, and its wall thickness is 0.01 m. It is placed in the center of the sand basin and fixed from the top, see Fig.16.

Fig. 16. Scale models in the laboratory tests: (a) before installing the TCT, (b) front view after the TCT is placed, (c) side view after the TCT is placed.

In this preliminary research, the scouring mitigation effect of a 3 kW three-bladed TCT was tested, of which the rotor diameter is 4.2 m. It was designed to operate in 12 m depth water, where the average tidal current speed is 0.75 m/s. In the experiments, the 1:12 scale model of such a TCT is suspended from the top of the monopile foundation. According to the Froude number calculated using (8), the water depth in the tank was set to be 1 m, and the average flow speed in the tank was controlled at about 0.22 m/s. The rotor diameter of the scale model was 0.35 m.

$$F_r = \frac{V}{\sqrt{gD}} \quad (8)$$

where V is flow speed, g is the acceleration of gravity, and D is Characteristic length.

The measurement of scour pits is very critical in the verification tests. At present, two measurement methods are popularly used. The first method is to estimate the size of the scour pit based on the pictures taken from outside the observation window. The accuracy of the estimation is highly dependent on the quality of the pictures. However, the practice has shown that it is very difficult to guarantee the quality of the pictures because the water will become cloudy due to the sands stirred by the vortices around the monopile. The second method is to drain all the water in the tank before measuring. However, the accuracy of the estimation cannot be guaranteed either by using this method because sand may backfill in the process [33,34]. For these reasons, a new scour pit measurement method is developed in this study. It is shown in Fig. 17.

(a)

(b)

Fig. 17. New scour pit measurement method: (a) rulers; and (b) lighting and video camera system.

The new scour pit measurement method is implemented via four rulers attached on the inner wall of the pipe, a digital video camera, a lighting system, a motor, and other auxiliaries placed in the pipe. The four rulers are attached in four directions, i.e. ruler #1 is for measuring the scour pit in front of the monopile foundation, ruler #3 is for measuring the scour pit behind the monopile foundation, and ruler #2 and ruler #4 are for measuring the scour pits on the two sides of the monopile foundation. The video camera is driven to rotate by the motor during the tests. The rated speed of the motor is 7 rev/min, but the speed can be adjusted more slowly as needed. When the camera rotates, it will record the depth of the scout pit in all directions. Then in this way, the initiation and development of the scour pit around the pipe can be accurately recorded.

5.2. Testing results and discussion

First of all, the experiments were conducted to verify the conclusions obtained based on the numerical calculation results shown in Fig.9. The Experimental parameters are shown in Table 3.

Table 3. Experimental parameters.

Average Flow speed in the tank	0.22 m/s
Experimental water depth	1 m
The median size of sand (d_{50})	0.2 mm
The rotational diameter of the TCT model	0.365 m
The rotational speed of TCT	10 rev/min

Herein, it is worth noting that the rotational speed of the TCT may have a significant influence on its scour mitigation effect. Considering the TCT being tested would show inconsistent rotating speeds due to the complex flow pattern in the tank and the inconsistent

rotational speeds of the TCT may affect the reliability of test results, a DC motor is installed in the nacelle of the scale model to control the rotational speed of the model. During the tests, a constant TCT rotational speed of 10 rev/min and a constant tidal current speed of 0.22 m/s are maintained all the time. Using the Froude number equation described by (8) and the data provided in Section 5.1 and those listed in Table 3, it can be readily known that rotational speed of 10 rev/min of the TCT model corresponds to a rotational speed of 2.89 rev/min of the full scale TCT. In real life, such a low speed is actually meaningless for reducing the scour around the monopile foundation of an OWT. However, if the effect of the normal speed, 17-20 rev/min, of a full scale TCT is to be replicated in the tank, the rotor speed of the scale model must be maintained at 59-69 rev/min. With the aid of the DC motor installed in the nacelle of the scale model, there is no problem to achieve such a high rotor speed. However, in the test, the scale model of the TCT was installed just above the artificial seabed. When the rotor of the scale model rotates at high speeds, its blades will cause additional erosion of the artificial seabed, which may significantly affect the assessment of the scouring mitigation effect of the TCT via energy absorption and flow disturbance. Therefore, based on these considerations, the rotor speed of the scale model was maintained at 10 rev/min during the laboratory test.

After the tank was filled with 1 m depth water and when the average flow speed in the tank was controlled at about 0.22 m/s, the growth of the scour pit in the four directions was monitored over time. All measurement results obtained within the first 180 min are shown in Fig. 18.

Fig. 18. Growth of the scour pit over time.

416

417 From Fig. 18, it is found that after the test went on for 180 min, the depths of the scour pit
418 in all four circumferential directions tend to converge. In addition, it is seen that the values of
419 the scour pit depths on the two sides of the monopile foundation are always larger than the
420 corresponding scour pit depths in front of and behind the monopile. Such observation agrees
421 very well with the conclusion drawn based on the calculation results shown in Fig.9. This, to a
422 certain extent, proves the correctness of the simulation results given above, therefore the
423 reliability of the conclusions drawn based on them. Besides, it is interestingly seen that the
424 scour pit depth behind the monopile decreases in the first 20 minutes, keeps the approximately
425 same depth in the second 20 minutes, and then turns to increase slowly after that. The scour pit
426 depth will reach about 0 cm 10 more minutes later. This reveals that, unlike the growth of the
427 scour pit in the other three directions, the scour pit behind the monopile will grow with a time
428 lag. The pairs of anti-rotational vortices observed behind the monopile account for this
429 interesting phenomenon.

430 Subsequently, as did in the numerical study in Section 4, the optimal installation position
431 of the TCT is also investigated in the laboratory tests. Firstly, the influence of the installation
432 distance of TCT in front of the monopile on seabed scour is investigated. In the experiments,
433 the water depth in the tank is still 1 m, the average flow speed is controlled still at about 0.22
434 m/s. Install the TCT at 10 cm above the surface of the sand basin. When the TCT is placed
435 respectively at 10 cm, 20 cm, 30 cm, 40 cm, and 50 cm, the scour pit depths in the four directions
436 are measured after the monopile is eroded by the water for 180 minutes. The measurement
437 results are shown in Fig.19, where the measurement results of the scour pit depth behind the
438 monopile are not plotted as they are very small in value.

Fig. 19. Depths of scour pit measured when the TCT is at different locations.

Since the growth of the scour pit is highly dependent on the shear stress on the seabed surface, Fig. 19 is compared with Fig. 10 in the process of data analysis. It is found that the curves in the two figures show similar variation tendencies although they represent the tendencies of different variables. With the increase of the installation distance, all curves in both figures decrease first and then turn to increase after reaching the minimum values when the TCT at distance 30 cm. This suggests that the installation distance of the TCT in front of the monopile foundation does have a significant influence on seabed scour. Moreover, an optimal installation distance of the TCT in front of the monopile does exist. It is 30 cm in the scenarios considered in this study.

Secondly, the influence of the installation height of TCT above the ground surface of the sand basin on seabed scour is investigated. In the experiments, the water depth in the tank is still 1 m, the average flow speed is controlled still at about 0.22 m/s. Since Fig.19 has shown that the optimal installation distance is 30 cm, the TCT is placed at 30 cm in front of the monopile in the experiments. When the TCT is placed respectively at 5 cm, 10 cm, 15 cm, 20 cm, and 25 cm above the surface of the sand basin, the scour pit depths in different directions are measured after the monopile is eroded by the water for 180 minutes. The measurement results are shown in Fig.20.

Fig. 20. Scour pit depths measured when the TCT is at different installation heights.

Through comparing Fig. 20 and Fig. 12, it is found that the variation tendencies of the curves in the two figures against the increase of the TCT installation height are very similar. With the increase of the installation height of the TCT, the curves decrease first and then turn to increase after the curves reach the minimum scour depth at installation height 10 cm. This suggests that the installation height of the TCT does have a significant influence on seabed scour. Moreover, an optimal installation height of the TCT does exist. It is 10 cm in the scenarios considered in this study.

6. Conclusion

A new scouring mitigation measure using TCT was studied in this paper. Compared with the existing anti-scouring technologies that have been reported in the open literature, the proposed TCT-based technique is easier to deploy and decommission. Moreover, the TCT can generate green electricity whilst protecting the monopile foundation of the OWT. Therefore, in theory, it has more potential to reduce the Levelized Cost of the offshore wind project.

The numerical and experimental research has shown that the TCT does have the potential to reduce scouring when it is placed in front of the monopile foundation of an OWT. This is because the operation of the rotor of the TCT not only absorb energy from the tidal current but disturb the motion of the water flow, both of which will reduce the strength of vortices around the monopile foundation of the OWT, thereby reducing the scouring around it. However, the

research has shown that the scour mitigation effect of the TCT is highly dependent on its installation position. When the TCT is properly installed in front of the monopile foundation, the maximum shear stress on the seabed surface can be reduced by 8%, and correspondingly, the maximum scour pit depth is reduced by 42%.

Although the TCT has shown a promising application to mitigating scouring, its practical application in offshore wind farms is still challenging. For example, the TCT is fully submerged in corrosive seawater. Its reliability in the long service life may be an issue. Once a fault was developed in it, the maintenance of the TCT will be quite difficult and expensive. In addition, the TCT is placed above the seabed. The rotation of the TCT blades may cause additional seabed erosion issues in the local area. Finally, the scour mitigation effect of the TCT should also be affected by the tidal current speed and the rotational speed of the TCT. Therefore, the rotational speed of the TCT should be carefully selected when the TCT is operated under different tidal current conditions. However, the optimal rotational speeds of the TCT corresponding to different tidal current speeds have not been investigated in this preliminary research. All these issues may hinder the practical application of the proposed technology. To address these issues, further in-depth research will be conducted at the next step, and the relevant research results will be reported in a separate paper.

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