Study on Local Sediment Scour and Stress State of Submarine Cables in Offshore Wind Farms

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Abstract. The laying of submarine cables will destroy the local seabed topography, leading to changes in the submarine hydrodynamic boundary, which will cause the local unbalanced sediment transport phenomenon when the submarine cable is buried. When the submarine cable begins to be exposed or the topography changes greatly, the scour phenomenon will be more severe. This article starts from the safety and stability of the submarine cable during the operation and maintenance of the 200MW offshore wind farm in Xuwen Wailuo, Guangdong Province, China and refers to the partial scour of the submarine cable in the “Southern Main Grid and Hainan Power Grid Second Interconnection Project” near the site near the Qiongzhou Strait. In this case, the measured ocean hydrological data at the site is used as the input condition, and Fluent is used to establish a refined hydrodynamic model of the submarine cable scour, to simulate the development process of the submarine cable scour of the wind farm under real sea conditions, and to perform the force analysis after the submarine cable is exposed. These will provide a certain scientific basis for ensuring the safe and stable operation of submarine cables during wind farm operation and maintenance.

1. Introduction

The local scour of the submarine cable has an important influence on the stability of the submarine cable. Understanding the scour process of submarine cables and predicting the scour of submarine cables are of great significance to the design of submarine cables [1]. According to the requirements of the specification: underwater cables should not be suspended in water, the burial depth of shallow water area should not be less than 0.5 m, and the burial depth of deep water channel area should not be less than 2 m[2-4]. The design of the Hainan Power Grid interconnection project has followed the specification requirements; the design value of the buried depth of the submarine cable protection is 1.5-2 m[5]. The Hainan Networking System, which was built and used in 2009, has been carrying out various protections in the following years. However, a special study on the scour of the submarine cable in the Qiongzhou Strait in 2019 showed that the depth in middle part of the submarine cable in this area and near the south coast becomes shallower, and some submarine cables have been partially exposed or even suspended in water. There was a special case of submarine cable exposure during this on-site exploration. The submarine cable was partially exposed, and the north and south sides of the exposed location formed a slope of approximately 0.75 due to scour [6]. Based on the preliminary hydrological observation data of the 200MW offshore wind farm in Xuwen Wailuo, Guangdong Province, China and the special terrain model, this paper uses Fluent to simulate the scour trend of the submarine cable of the wind farm under this special terrain, and calculates the force on the submarine cable through OrcaFlex. These will
provide a certain scientific basis for ensuring the safe and stable operation of submarine cables during wind farm operation and maintenance.

2. Numerical model
The Euler multiphase flow model analyzes various fluids or fluids of each phase by solving the flow equations of each phase separately. The different phases are processed into interpenetrating continuous media. Since the volume occupied by one phase cannot be occupied by others, the concept of phasic volume fraction is introduced.

2.1. Governing equations
The continuity equation
\[ \frac{\partial}{\partial t}(\alpha_t \rho_t) + \nabla \cdot (\alpha_t \rho_t \mathbf{v}_t) = 0 \]  
where \( t = w, s \) and \( \alpha_w + \alpha_s = 1 \), \( \alpha_w, \alpha_s \) are the volume fractions for water and sediment and \( \rho_w, \rho_s \) are the physical densities of water and sediment, respectively.

Momentum equations for water-water and water-sediment interactions
\[ \frac{\partial}{\partial t}(\alpha_w \rho_w \mathbf{v}_w) + \nabla \cdot (\alpha_w \rho_w \mathbf{v}_w \mathbf{v}_w) = -\alpha_w \nabla p + \nabla \cdot \tau_w + \alpha_w \rho_w g + K_{sw}(\mathbf{v}_s - \mathbf{v}_w) \]  
\[ \frac{\partial}{\partial t}(\alpha_s \rho_s \mathbf{v}_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{v}_s \mathbf{v}_s) = -\alpha_s \nabla p - \nabla \cdot \tau_s + \alpha_s \rho_s g + K_{sw}(\mathbf{v}_w - \mathbf{v}_s) \]  
where \( \mathbf{v}_w, \mathbf{v}_s \) are the velocities of water and sediment, \( p \) is the pressure shared by the two phases, and \( g \) is the acceleration due to gravity.

Stress tensor for the sediment phase is given by
\[ \tau_s = \alpha_s u_s (\nabla \mathbf{v}_s + \nabla \mathbf{v}_s^T) + \alpha_s (\lambda_s - 2u_s/3) \nabla \cdot \mathbf{v}_s \]  
Stress tensor for the water phase is given by
\[ \tau_w = \alpha_w u_w (\nabla \mathbf{v}_w + \nabla \mathbf{v}_w^T) \]  
where \( \tau \) is an identity tensor. The sediment bulk viscosity accounts for the resistance of the granular particles to compression and expansion, and it has the following form:
\[ \lambda_s = 4 \alpha_s \rho_s d_s g_{0,ss}(1 + e_{ss})(\Theta_s/\pi)^{1/2}/3 \]  
Here \( d_s \) is the diameter of sediment and \( e_{ss} \) is a restitution coefficient. \( g_{0,ss} = [1 - (\alpha_s/\alpha_s,\max)^{1/2}]^{-1} \) is a radial distribution function defined as the probability of a particle touching another particle. The maximum value of the sediment volume fraction is \( \alpha_s,\max = 0.63 \). \( \Theta_s \) is granular temperature proportional to the kinetic energy of the fluctuating particle motion.

In equation (5), \( u_w \) is shear viscosity of water. The collisional and kinetic parts, and the optional frictional part, are added to give the sediments shear viscosity
\[ u_s = u_{s,\text{coll}} + u_{s,\text{kim}} + u_{s, \text{fr}} \]  
where the collisional part of the shear viscosity is modeled as
\[ u_{s,\text{coll}} = 0.8 \alpha_s \rho_s d_s g_{0,ss}(1 + e_{ss})(\Theta_s/\pi)^{1/2} \]  
The expression for the kinetic part is
\[ u_{s,\text{kim}} = \alpha_s \rho_s d_s \sqrt{\Theta_s}(1 + 0.4(1 + e_{ss})(3e_{ss} - 1)\alpha_s g_{0,ss})/[6(3 - e_{ss})] \]  
In dense flows at low shearing rate, where the volume fraction of the secondary phase, namely sediment phase, approaches its packing limit, the formation of the stress is mainly due to friction between particles. The frictional viscosity can be estimated by
\[ u_{s,\text{fr}} = 0.5 \rho_s \sin \phi / \sqrt{2D} \]  
Here the sediment pressure:
\[ P_s = \alpha_s \rho_s \Theta_s + 2 \rho_s (1 + e_{ss}) \alpha_s g_{0,ss} \Theta_s \]  
And \( \phi \) is the angle of internal friction. \( 2D \) is the second invariant of the deviatoric stress tensor. The water-sediment exchange coefficient has the form
\[ K_{sw} = K_{ws} = 0.75 \alpha_s \alpha_w \rho_w C_D (Re_s/Re_s) \left| \mathbf{v}_s - \mathbf{v}_w \right| / (\mu_s d_s) \]  
where drag coefficient \( C_D = (0.63 + 4.8/\sqrt{Re_s/Re_s})^2 \), relative Reynolds number between water and sediment \( Re_s = \rho_w d_s \left| \mathbf{v}_s - \mathbf{v}_w \right| / \mu_w \). The terminal velocity correlation for the sediment phase
\[ V_{r,s} = 0.5\{A - 0.06Re_s + [(0.06Re_s^2) + 0.12Re_s(2B - A) + A^2]^{1/2}\} \]  

(13)

Where \( A = \alpha_w^{1.14} \) and \( B = 0.8\alpha_w^{1.28} \) for \( \alpha_w \leq 0.85 \), and \( B = \alpha_w^{2.65} \) for \( \alpha_w > 0.85 \).

2.2. Model parameters and boundary conditions

According to the characteristic topography after the scour of the Qiongzhou Strait, the cable in the model is buried by two symmetrical small sand dunes which slope is 0.75 from north to south, and the maximum buried depth of the submarine cable is 1500mm. The bottom top view of the model is shown in Figure 1 and its | I - I | and | II - II | section as shown in Figure 2 and Figure 3.

![Figure 1](image1.png)

**Figure 1.** The bottom top view of the model (unit: mm).

![Figure 2](image2.png)

**Figure 2.** The | I - I | section of the bottom model (unit: mm).

![Figure 3](image3.png)

**Figure 3.** The | II - II | section of the bottom model (unit: mm).

The model is divided by a tetrahedral grid, and the grid around the submarine cable is encrypted. The overall grid is divided into 1219133 units as shown in Figure 4. The two-dimensional boundary conditions of the model | I - I | section and the exposed center of the submarine cable are shown in Figure 5 and Figure 6.

We use the Fluent UDF module to import the flow velocity distribution formula. Refer to the numerical simulation method of Leeuwenstein W, Wind HG [6] and Li FJ, Cheng L [7]. Here, Euler polynomial flow model and k-\( \varepsilon \) turbulence model are used for simulation.

Due to the symmetry of the model, only half of the submarine cable is set with monitoring points. The monitoring points are all located at a distance of \( D=140\text{mm} \) below the center line of the submarine cable. The distribution diagram is shown in Figure 7. Here, 12 detection points are set at the bottom of the submarine cable to view the change of the sediment volume fraction. Since the coordinates of P0 directly below the exposed center of the submarine cable in the model are (0, 0.86, 6), the coordinates of the remaining points are shown in Table 1.

![Figure 4](image4.png)

3. Hydrological environment

The average water depth of the Xuwen offshore wind farm site is about 30m, the \( D_{50} \) of the sediment at the bottom is 0.000264m, and the water moisture content of surface sediment is 31.86%. The velocity distribution at the bottom 6m water depth is used as the velocity inlet condition of the model. The ocean current in this observation area has the characteristics that the flow velocity of the rising tide is lower than the flow velocity of the ebb tide and the average current velocity in winter is the largest throughout the year [8].
Figure 4. Model meshing diagram.

Figure 5. Two-dimensional boundary thumbnail image of 1-1 section of the model (unit: mm).

Figure 6. Two-dimensional boundary thumbnail image of the exposed center of the submarine cable (unit: mm).
The model only considers the scour effect of the one-way incoming flow. The corresponding data scatter diagram of the rising tide velocity and the water depth measured at a certain time in the winter at the bottom layer is shown in Figure 8. When the water depth is used as the independent variable to compare the fitting effects of polynomial, S-function and logarithmic function through Origin software, the best one is the S-function. The fitting result is shown in Figure 9, the S-function of the flow velocity along the depth of water is showed in equation (14).

\[ V_d = 0.67336 \exp\{- \exp\left[-0.50162(d - 0.52009)\right]\} \quad d \in (0, 6] \quad (14) \]

Where \( V_d \) (unit: m/s) is the flow velocity at the depth \( d \) of water, \( d \) (unit: m) is the depth of water.

Figure 8. The scatter diagram of the rising tide velocity and the water depth.

Figure 9. The S-function fitting effect diagram of flow velocity and depth of water.

4. Result analysis
4.1. Sediment scour analysis

There are many previous test results for pipeline scour simulation. The bottom of the pipeline which \( D=100 \text{mm} \) could be completely scoured out by the clear water to reach flush balance at a flow velocity of \( 0.5 \text{m/s} \) after \( 100 \text{min} \) [9]. The \( 0.5D \) position under the \( D=100 \) pipeline could be scoured out by the clear water in about \( 40 \text{min} \) at the flow velocity of \( 0.42 \text{m/s} \) and the scour tends to balance in \( 100-200 \text{min} \) [10]. The scour pit developed rapidly between \( 0 \text{ min} \) and \( 100 \text{ min} \) in the two-dimensional simulation scour experiment of different pipe diameters and during this simulation scour process, a sediment volume fraction of 0.5 was used as the water and sediment boundary [11]. However, there are still gaps in the simulation of the scour and force of the submarine cable in this special terrain.

The change of the sediment volume fraction of the model section at the position P0-P11 is shown in Figure 10, where the P line represents the boundary line where the sediment volume fraction is 0.5. The simulation environment and scour results of two-dimensional profile at P0 is similar to their simulation result [9-11]. Since the position of P0 in the model canyon, it’s faster to be scoured at 0.5D than their model.

According to the results, we can obtain the time \( T \) when the sediment volume fraction of each monitoring point to reach 0.5. Through the symmetry of the model, the suspended length of the submarine cable at the corresponding time \( L=2(6-Z) \), where \( Z \) is the \( Z \) coordinate of the corresponding monitoring point. Numerical values and calculation results are shown in Table 2. The fitting curve of the time \( T \) and the suspended length \( L \) of the submarine cable obtained from Table 2 are shown in Figure 11. According to the data distribution in Table 2, by comparing the fitting models of polynomial, exponential function, logarithmic function, power function and S-function through Origin, the most reasonable function is power function. The curve of power function equation (15).

![Figure 10](image.png)

**Figure 10.** Variation curve of sediment volume fraction at P0-P11 monitoring point at the bottom of the submarine cable.

| Point | \( T \) (m) | \( L \) (m) |
|-------|-------------|-------------|
| P0    | 33.83       | 0           |
| P1    | 38.09       | 0.8         |
| P2    | 41.50       | 1.6         |
| P3    | 44.47       | 2.4         |
| P4    | 52.91       | 3.2         |
| P5    | 57.98       | 4           |
| P6    | 60.95       | 4.8         |
| P7    | 62.49       | 5.6         |
Figure 11. Distribution and fitting diagram between the suspended length and the corresponding time of the submarine cable at P0-P11 monitoring points.

\[ L_t = 5.90608 \times 10^{-8}(1+T)^{4.47675} \quad T \in (33, 70) \]

Where \( L_t \) (unit: m) is the suspended length of submarine cable, \( T \) (unit: min) is the time.

The three-dimensional and two-dimensional water-sediment boundary diagram with sediment volume fraction above 0.5 at 200 min is shown in Figure 12 and Figure 13. At this time, the depth of the scour pit at the bottom of the submarine cable is 0.6D. Irregular scouring pits begin to form at about 4D on the incoming flow side, and dunes with a height of about 0.5D begin to form at D on the back side. And then gradually level off.

Figure 12. Three-dimensional model of the isovolume with sediment.
4.2. Force analysis
After scour for 200 minutes, we set a velocity observation line at the distance D in the front of the submarine cable, and its position diagram is shown in Figure 14. The flow velocity distribution at 200 min at the observation line is shown in Figure 15.

![Figure 14. Position diagram of observation line.](image)
According to the terrain scoured at this time, roughly the same seabed surface is drawn in OrcaFlex. The length of submarine cable which ends have been fixed is 12m. The three-dimensional model is shown in Figure 16. Here, the flow velocity of the submarine incoming flow is 0.35m/s, the axial tensile stiffness of the submarine cable is $EA=1.86\times10^8$, the gravity in the water is 320N/m, and the tensile stress at yield is 87.5KN [12]. At this time, the flow velocity is greater than the maximum flow velocity in Figure 15, the effective tensile stress of the submarine cable obtained by simulation is shown in Figure 17, where the max effective tensile stress is 8.3295KN.

**Figure 15.** The flow velocity distribution at observation line.

**Figure 16.** The three-dimensional model of submarine in OrcaFlex

**Figure 17.** The effective tensile stress of the submarine cable changes with the direction of the incoming flow.
5. Conclusions
Submarine cable scour is a complex process. Different topography and hydrological environment have a greater impact on the scour process and speed. In this hydrological environment and model, the maximum scour depth is about 0.6D, and the scouring pit width is about 5D. Behind the cable, small sand dunes of about 0.5D height are formed, and the scour gradually tends to balance after 100 minutes. The existence of two sand dunes accelerates the scouring speed of the exposed point of the middle submarine cable, but as time changes, the scouring progress on both sides will eventually be roughly synchronized with the center.
On this special seafloor where the current velocity is 0.35m/s, the maximum effective tensile stress of the submarine cable is 8.3295KN during the change of time and direction of the incoming current in OrcaFlex. In the future construction of wind farms, if similar terrains appear, they must be dealt with as soon as possible to avoid accumulated damage caused by vortex-induced vibration under long-term scour.

6. References
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