Orthogonal Optimization Design of Scour Protection Device with Flexible Material for Pile Foundation

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Abstract. To apply the scour protection device with the flexible material developed by the author to engineering practice, orthogonal optimization design of the device for a fixed offshore platform in Chengdao Oilfield as a case study was presented. The influences of main design parameters, such as pile diameter, thickness of flexible material and elastic modulus of flexible material on the protective effect of the device were studied by two-way fluid-solid interaction numerical simulation based on ANSYS workbench platform. Then, the optimal design plan of the scour protection device with flexible material was determined. Furthermore, by comparing and contrasting the results of the flow field calculation for the pile legs with versus without protective devices were compared and analysed, the device’s good effective protection effect functionality was demonstrated. The research results will shed light on the practical engineering design of the flexible energy dissipation guiding antiscour device.

1. Introduction
Local scour around the piles is one of the common problems in pile-based hydraulic structures, affecting the safety of the structures, such as bridges, wharfs, jackup platforms and offshore wind power platforms [1-3]. To ensure the safe operation of pile-based hydraulic structures, addressing the limitations of existing antiscour technologies, the author proposed a new scour protection device [4], Flexible Energy Dissipation and Diversion Antiscour Device (FEDD). Figure 1 illustrates the innovative device for scour prevention. As indicated in the figure, component 1 is the flexible sheath; part 2 is the rigid baffle plate, which includes an annular retainer (4) and a short casing (5). Component 3 is a flexible pad; part 6 through 10 are a nylon fibula, anchor ropes, anchors, pile, and seabed, respectively.

Figure 1. Schematic diagram of FEDD [4]
(1 flexible sheath; 2 rigid baffle plate including 4 annular retainer and 5 short casing; 3 flexible pad; 6 nylon fibula; 7 anchor ropes; 8 anchors; 9 pile; 10 seabed)
As shown in Figure 1, the FEDD uses flexible material to reduce the speed of each part of the flow field and change the flow pattern around the pile, thereby fundamentally solving the problem of local scour of pile foundations, improving the foundation stability and prolonging the service life-span of the platforms. It is the first step to put forward a design project in order to apply FEDD to engineering practice. However, due to without engineering design experience of the FEDD, a trial-and-error process of traditional design method is required to obtain a feasible design scheme of the FEDD that meets the requirements of the standard and the user. The process will make design cycle long, and make the selection of parameters subjective and random, which lacks a robust of theoretical basis. More importantly, the scheme obtained is not the optimal one and cannot guarantee the effectiveness and economy of its engineering application. On the other hand, orthogonal optimization design method enjoys not only rapid and accurate parameter selection, but also high design efficiency and quality. In sum, it is necessary to study orthogonal optimization design of the FEDD in order to ensure the effective engineering application.

In this paper, taking the fixed offshore platform in literature [4] as the study case, different physical models were set up according to the orthogonal test scheme. The fluid-solid coupling numerical simulations of the pile legs with versus without a FEDD were carried out. The optimization combination of parameters of the FEDD was determined according to the statistical analysis of the orthogonal test. Furthermore, the protection effect of the device was confirmed by comparing and contrasting the images obtained from numerical simulations.

2. Theory and method

2.1. Fluid governing equations
Fluid flow follows three physical conservation laws, namely, the conservation laws of mass, momentum and energy. For general compressible Newtonian fluids, the conservation laws can be described by the mass conservation equation and the momentum conservation equation as follows [5]. The mass conservation equation can be written as

$$\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f v) = 0$$

(1)

The momentum conservation equation is derived as below

$$\frac{\partial \rho_f v}{\partial t} + \nabla \cdot (\rho_f vv - \tau_f) = f_f$$

(2)

where $t$, $f_f$, $\rho_f$, $v$, $\tau_f$ represent time, body force vector, fluid density, fluid velocity vector, fluid shear tensor, respectively, where $\tau_f$ can be defined as

$$\tau_f = (-p + \mu \nabla \cdot v)I + 2\mu e$$

(3)

where $p$, $\mu$, $e$ represent fluid pressure, dynamic viscosity and velocity stress tensor, respectively.

2.2. Solid governing equation
The conservation equation of the solid part describes the structural displacement state caused by fluid motion, which is obtained by Newton's second law.

$$\rho_s \ddot{d}_s = \nabla \cdot \sigma_s + f_s$$

(4)

where $\rho_s$, $\ddot{d}_s$, $\sigma_s$, $f_s$ represent solid density, local acceleration vector of solid domain, Cauchy stress tensor, volume force tensor, respectively.

2.3. Fluid-solid coupling equations
On the fluid-solid coupling interface, the three conditions of dynamics, kinematics and fluid velocity are satisfied [5]. In other words, the stress, displacement and velocity of the fluid and the solid keep conserved.
\[
\begin{align*}
\tau_f &= \tau_s \\
 d_f &= d_s \\
 v_f &= v_s
\end{align*}
\]  

(5)

where subscripts \( f \) and \( s \) are the fluid and the solid, \( \tau_f \) and \( \tau_s \) are fluid stress and solid stress on the fluid-solid boundary, \( d_f \) and \( d_s \) refer to fluid displacement and solid displacement, \( v_f \) and \( v_s \) are fluid velocity and solid velocity, respectively.

3. Numerical simulation of flow field around the pile

3.1. Material parameters

The material parameters of the pile leg and the FEDD of the pile-based platform operated in the Bohai Sea area were specified in Table 1. Nowadays, it is still difficult for two-way fluid-solid interaction numerical calculation to solve highly nonlinear problems due to its complexity [5]; therefore the models and the materials were simplified for calculations. The simplified model [4] of flexible materials only covered on the pile leg being used, while the materials of the pile leg and its cladding were both assumed as isotropic elastic.

| Parameter | Material          | Density (g/cm\(^3\)) | Elasticity modulus (MPa) | Poisson’s ratio | Damping coefficient |
|-----------|-------------------|-----------------------|--------------------------|-----------------|---------------------|
| Pile leg  | API 5L X60 steel  | 7.85                  | 207 000                 | 0.3             | /                   |
| Cladding  | Silicone Rubber   | 1.15                  | 0.5                     | 0.45            | 0.3                 |

3.2. Establishing of the flow field domain

The domain size of the three-dimensional flow field near the bed around the pile for each case was set to be \( 20D \times 10D \times 6D \), where \( D \) was the pile’s diameter. The inlet was a velocity inlet boundary. The outlet was a free outflow boundary. The bottom bed surface was a non-slip wall boundary. The top along with other surfaces was a symmetrical boundary; The contact surface between the fluid and the solid was set as no-slip wall surface in the flow field analysis, while it was set as fluid-solid interface (i.e. FSI) when the data were transmitted. According to the engineering practices, the pile was simplified to a vertical cantilever cylinder with a fixed constraint on the bottom surface.

3.3. Meshing

For the fluid domain, nine-zone cut method [6] and the structured hexahedral mesh [6] was adopted. The mesh quality was improved by local refinement around the cylinder. There were 406 728 grids for the entire flow field. For the solid domain, the regular hexahedral mesh was established by the sweep method. The schematic diagrams of the meshing of the fluid and the solid were illustrated in Figure 2 and Figure 3, respectively.

![Figure 2. 3D flow field model grid.](image)

![Figure 3. 3D cylinder model grid.](image)
3.4. Flow-solid interaction numerical simulation

Large deformation of the flexible material in the flow field will bring about significant changes in the fluid distribution; therefore, the analysis of flow field characteristics around the pile installed the FEDD device is a typical two-way fluid-solid interaction numerical calculation problem. For the convenience of comparison, the case for the pile of FEDD device was also used two-way fluid-solid interaction numerical calculation method. All simulations were carried out on ANSYS workbench platform. The two-way fluid-solid interaction simulations were achieved through three modules. Therein, fluid analysis was set up in FLUENT module; structural analysis was set up in Transient Structural module; while data exchange between the flow field and the structure field was performed in System Coupling module. The turbulent flow field was simulated using the Large Eddy Simulation (LES) model [7] which has been proved to be the optimal method for the problems of three-dimensional flow pasting circular cylinder. The solid deformation was calculated using geometric large deformation method, and the coupling of the flow field and the cylinder adopts dynamic mesh technology. The time step (Δt) was taken as 0.05 seconds and the calculation period was 30 seconds in order to obtain a fully developed flow field.

4. Orthogonal test and data analysis

4.1. Orthogonal test

Orthogonal test method [8] is a high-efficiency design method commonly used in multifactor optimization problems. It uses mathematical statistics and the principle of orthogonality and designs the test scheme using the orthogonal table [9]. The selected experiments not only have the characteristics of being balanced, dispersed, neat and comparable, but also have fewer experiments and more reliable results. Additionally, the data analysis of the orthogonal test is also simple and clear. Through analysing the orthogonal table and the visual analysis curves, the influence of each factor on the experimental index was computed, and then the primary factors and the secondary ones were obtained. As a result, the optimum parameter combination for the FEDD was obtained.

4.2. Test scheme

There are many factors affecting the effect of scour protection of the FEDD, and some of them are controllable. According to the engineering practice and the characteristics of the FEDD, three adjustable parameters, i.e., the diameter of the pile, the thickness of the flexible material and the elastic modulus of the flexible material, were selected as the test factors of the orthogonal test. According to the relevant specification requirements and engineering experience, two levels were selected for each factor. The factors and corresponding levels of the orthogonal test were shown in Table 2. Therein, A represents the diameter of the pile, B is the thickness of the flexible material, and C is the elastic modulus of the flexible material.

| Table 2. Factor levels of orthogonal numerical test |
|---------------------------------|
| Test factors                        |
| level | diameter of pile /m | thickness of flexible material /m | elastic modulus of flexible material / MPa |
|-------|---------------------|----------------------------------|--------------------------------------------|
| 1     | A                   | B                               | C                                           |
| 2     | 1.5                 | 0.2                             | 0.5                                        |
| 2     | 2.0                 | 0.4                             | 500                                        |

The orthogonal experiment scheme L4 (2^3) of 3-factors with 2-levels was designed, disregarding the interaction among the factors. There was a total of 4 trials, half of the amount of comprehensive experiments needed (2^3 = 8), which greatly reduced the experiment time used to improve the productivity. One numerical simulation was taken as one test, and the specific test plan was in Table 3.
Table 3. Design of orthogonal test scheme

| No. of test | No. of factors |
|-------------|----------------|
|             | A   | B   | C   |
| 1           | 1   | 1   | 1   |
| 2           | 1   | 2   | 2   |
| 3           | 2   | 1   | 2   |
| 4           | 2   | 2   | 1   |

4.3. Results and analysis of Orthogonal test

The average velocity of the near-bottom wake can reflect the scour intensity in the wake. The smaller the average velocity is, the greater the impact of weakening scours in the wake is, and the better the antiscour effect of the FEDD will be. Therefore, the average velocity of the near-bottom wake in the range of twice the diameter of the pile (2D) was selected as the benchmark index of the orthogonal test, named as D (its unit is m/s, meters per second). The numerical simulations were carried out according to the orthogonal test scheme, and the simulation results of each case were obtained. Table 4 indicates the results of the evaluation index D.

Table 4. Results of average speed of near-bottom wake

| No. of test | A   | B   | C   | D   |
|-------------|-----|-----|-----|-----|
| 1           | 1.5 | 0.2 | 0.5 | 0.46|
| 2           | 1.5 | 0.4 | 500 | -0.32|
| 3           | 2.0 | 0.2 | 500 | 1.80|
| 4           | 2.0 | 0.4 | 0.5 | -0.47|

The test results were analysed using the direct-viewing analysis method [10]. Direct-viewing analysis method obtains the primary and secondary factors, the optimal level and the optimal combination of the factors by calculating the mean value and the range of each factor. The mean values are used to determine the optimal level and optimal combination of each factor. The ranges reflect the influence of the factor levels on the test index and are used to determine the primary and the secondary sequence of the factors. The larger the range is, the greater the influence of the level change of the factor on the index is, and consequently the more significant the factor will be.

The analysis results of the orthogonal test were displayed in Table 5. The mean values $k_i$ ($i=1, 2$) were obtained from the test indexes of each factor corresponding to its $i$th level, and then the ranges, $Rs$ [8] of the test index corresponding to each factor were calculated. In order to analyze the effect of the three test factors on the test index more intuitively, the visual analysis curves were depicted in Figure 4 according to the numerical results in Table 5.

Table 5. Analysis results of orthogonal test

| Test index | Analysis results | Factors |
|------------|------------------|---------|
| D          | $k_1$            | A   | B   | C    |
|            | 0.07             | 1.13 | -0.005|
|            | $k_2$            | 0.665| -0.395| 0.74 |
|            | $R$              | 0.595| 1.525| 0.745|
| Order of importance of factors | 3 | 1 | 2 |
| optimal level of factors  | A1 | B2 | C1 |
It can be seen from Table 5 and Figure 4:

(1) The larger the pile diameter (A) is, the greater the average speed of the wake in 2D range near the bottom of the pile is, and subsequently, the better antiscour effect of the FEDD would be. The larger the thickness of the flexible material (B) is, the lower the average speed of the wake is, and then the better antiscour effect of the FEDD would be. Finally, the smaller the elastic modulus of the flexible material (C) is, the lower the average speed of the wake is, and the better antiscour effect of the FEDD would be.

(2) According to the range values and the slope of the visual analysis curves for showing the effect of various factors on scour intensity in the wake, the order of the influence of the three factors on the test index could be determined. Amongst them, the range of the thickness of the flexible material (B) was the largest, and the slope of the curve was the greatest; the range of the elastic modulus of the flexible material (C) was secondary; while the range of the diameter of the pile (A) was the smallest. Therefore, it indicates that the parameter of the thickness of the flexible material is the most sensitive and important factor, and thus, its variation has the greatest influence on the protective effect of the FEDD. The sensitivity of the elastic modulus of the flexible material (C) was medium, and the influence of the diameter of the pile (A) was the least. The importance of the three design parameters is ranked from large to small as following: flexible material thickness (B) > flexible material elastic modulus (C) > pile diameter (A).

(3) The optimum combination of the parameters is determined according to the mean values of the test indexes. The optimal levels of the three factors A, B, C are A1, B2, and C1, respectively. Therefore, the optimal combination is A1B2C1. That is, the physical parameters of the flexible material of the FEDD for the 2 meter-diameter pile are optimized to the thickness of 400 mm and the elastic modulus of 0.5 MPa.

5. Protective effect of the FEDD

Figures 5 through 7 are contours of velocity distribution, vectors of wall shear stress, and contours of eddy viscosity around the pile with (right figures) and without (left figures) the FEDD installed,
respectively. In this section, protective effect of the device was investigated from various aspects through comparative analysis as below.

5.1. Contours of velocity distribution

Figure 5 illustrates contours of velocity distribution around the pile near the seabed. Comparing the right against the left images where they are the pile with and without the FEDD, it can be seen that the flow around the leg was affected by the flexible guard device. To be specific, the flow pattern, velocity distribution and flow velocity around the leg were all altered apparently.

![Figure 5. Contours of velocity distribution around the pile.](image)

For a pile-based structure without a protective device being installed, the flow pattern was changed near the pile compared with the original one because the structure blocked the approach flow and disturbed the equilibrium of the original flow field. And the maximum flow velocity on both sides of the pile reached 1.896 m/s, which was close to the wall of the pile leg. In contrast, with a FEDD being installed, the high-speed flow on both sides of the leg was reduced because the flexible material absorbed part of the kinetic energy of the flow, but high-speed flow appeared only in a very small area with the velocity 1.970 m/s close to the shoulders on both sides of the leg. This is due to numerical distortion since the speed value from the numerical calculation shown in figure superimposed the speed value of the deformation of the flexible material. The actual flow velocity should be subtracted from the deformation velocity of the flexible material. Thus, the flow velocity on both sides of the leg installed with the FEDD would be significantly less than that of the leg without the FEDD. Moreover, the region where the flow velocity was increased would also be significantly reduced.

Due to energy absorption and large deformation of the flexible material, the wake pattern was also significantly different. The flow velocity in the wake of the leg without the FEDD was significantly higher than that of the leg with the FEDD, and the wake range was larger and more sizable, so it was easier to erode the leg’s foundation soil. The flow velocity at the monitoring point behind the bare leg was 0.26 m/s, and the flow velocity at the monitoring point behind the coated leg was 0.13 m/s. It can be concluded that the FEDD has a good deceleration effect on the wake.

5.2. Vectors of wall shear stress

The magnitude of the wall shear stress is closely related to the severity of the seabed being scoured by the flow around the pile. It can be seen from Figure 6, the shear stress reached a maximum due to the influence of the horseshoe vortex on both sides of the upstream surface of the pile. Observing the left and the right figures, the shear stress of the coated leg was significantly smaller than that of the bare leg. Illustrating that the protective device led to a tremendous effect on reducing the horseshoe vortex on both sides of the pile, which was consistent with the comparison of the flow field pattern on both sides of the leg.
5.3. Contours of eddy viscosity
The momentum transfer of the vortex causes internal fluid friction. As the transport coefficient of turbulence, the eddy viscosity is the fluid resistance inside the turbulent flow. The Contours of eddy viscosities on the horizontal section and vertical middle section are shown in Figure 7 (a) and (b), respectively. As shown in the figures, the vorticity behind the leg without the FEDD was significantly greater than the counterpart, which was consistent with the comparison of the wake vortex flow pattern behind the leg in Figure 5.

From the comparative studies of Section 5.1 through 5.3, the author proves that the FEDD device can protect the pile from being scoured.

6. Concluding remarks
In this research, the optimization design of the new scour protection device FEDD developed in the previous studies was examined, and then the effectiveness of the device was demonstrated from several aspects through the comparative analysis of fluid-solid interaction numerical simulation results of the pile with and without a FEDD.
1) Through the orthogonal test and numerical simulation, the optimization scheme of the FEDD was provided, which shed light on how to improve the protection effect and economy of the focal devices.

2) In the numerical calculations, the cases with different parameters were modelled one after another, which requires significant labours. In order to simplify the parameter optimization design, it is necessary to study how to realize the continuous automatic adjustments and computations for all the models through computer programming, and then automatically perform the orthogonal test to obtain the optimal scheme. In that way, it will be convenient to conduct orthogonal tests with more factors and a wider range of factor levels, and realize real-time optimizing, and then the optimization scheme obtained can better meet the engineering requirements.

3) In the follow-up study, physical model tests and field tests are also recommended to further verify the reliability of the numerical simulation results in order to realize the industrialization of research results.

7. References
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