

**Research Article**

# **Modeling and parametric analysis of inter-array power cables in offshore wind farms**

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Received: May 23, 2026 / Revised: August 1, 2026 / Accepted: August 8, 2026

## **ABSTRACT**

This paper proposes a theoretical method for structural analysis of wind farm inter-array cables. By establishing a theoretical model for inter-array cables, the configuration, curvature, bending moment and tension distribution of the cables are obtained, and a parametric analysis is conducted. The entire cable is modeled as a series of continuous segments including buoyancy sections and suspended spans. Subsequently, equilibrium equations are established based on the principle of minimum potential energy. The finite difference method is adopted for spatial discretization, and the Newton-Raphson algorithm is utilized to realize iterative convergence of the nonlinear system. The analysis results are compared with those from OrcaFlex simulations to validate the feasibility and accuracy of the proposed method. Furthermore, a detailed parametric analysis is performed to investigate the effects of buoy length, spatial arrangement, and ocean current velocity on the mechanical properties of the cables. This method contributes to the structural analysis and layout design of inter-array cables in offshore wind farms.

## **KEYWORDS**

Inter-array cables, Theoretical model, Fully suspended cable, Parametric analysis

## 1. Introduction

In recent years, the global annual newly installed capacity of floating offshore wind power has steadily reached the gigawatt (GW)-class scale. Since 2021, global annual newly installed capacity has exceeded 8 GW for four consecutive years, indicating that this technology is advancing from the demonstration phase to large-scale application[1]. As a power transmission channel connecting wind turbine arrays and power grids, offshore wind farm cables account for approximately 20% of the total construction cost of offshore wind farms[2], and are also a core factor determining the full-life-cycle economic benefits (Zhang et al.; Xia et al.) [4]-[5]. Compared with cables used in traditional offshore oil and gas fields, offshore wind farm cables have much higher technical requirements in terms of operating voltage and structural diversity. These cables are responsible for power transmission at higher voltage levels. High voltage imposes stricter requirements on cable insulation, accessory design and electric field distribution, thereby bringing prominent technical challenges. In addition, such cables need to adapt to complex operating scenarios involving various layouts including the free-suspension cable configuration (Fig.1(a)) and the fully suspended cable configuration (Fig.1(b)). The above reasons make cables a vulnerable link of the whole system and result in frequent faults. Relevant studies show that cable failures cause nearly 80% of total financial losses and insurance claims in offshore wind projects[3], so cable design still faces critical theoretical and technical difficulties.

The configuration of offshore wind farm cables not only determines their mechanical properties but also affects their application scenarios. Common types of offshore wind farm cables include free-suspension cable configurations (Fig.1 (a)), as well as lazy-wave and steep wave cable configurations formed by attaching additional accessories. Such cables are mainly deployed in shallow sea waters to realize power transmission between offshore platforms and submarine substations. As the operating water depth increases, the cable laying length grows correspondingly. This type of cable encounters various engineering problems involving manufacturing costs, structural stress, underwater installation and long-distance power transmission [6]-[11]. In

addition, as shown in Fig.1 (b), there is a fully suspended cable structure for the inter-array layout of offshore wind farms [12]. This kind of cable realizes power transmission between offshore platforms, reduces the required cable length for connecting to submarine substations, and solves the problems caused by excessive cable length [13]-[14]. At present, the large-scale engineering applications of this structure remain limited. However, with the continuous increase of operating water depth, the research value becomes increasingly prominent.

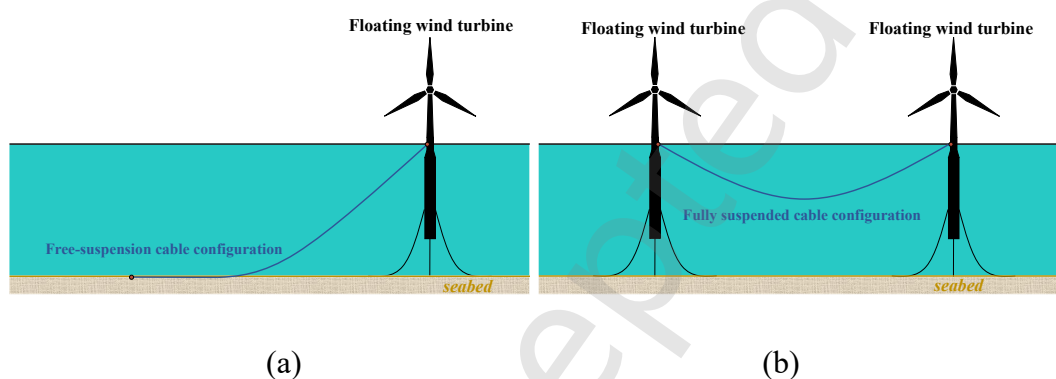


Fig.1 (a) Free-suspension cable configuration; (b) Fully suspended cable configuration.

For the fully suspended configuration of inter-array cables in floating offshore wind farms, it has become a popular research topic in recent years. Schnepf A et al.[15] proposed the fully suspended configuration for inter-array cables in floating offshore wind farms and analyzed the advantages and disadvantages of this configuration using OrcaFlex modeling. This cable configuration avoids friction caused by the seabed and reduces the tension on the cable, but longer cable segments are subjected to stronger ocean current loads. Therefore, an assessment of factors such as marine environmental conditions and cable configuration is required. Li D R et al. [16] evaluated the feasibility of the fully suspended inter-array cable system under extreme sea conditions and normal operating sea conditions through numerical simulations and scaled-down experiments. Schnepf A et al.[17] investigated the feasibility of suspending inter-array cables between two floating offshore wind turbines, and this configuration delivers cost savings compared with laying the cables on the seabed. Based on the commercial software OrcaFlex, Beier D et al.[18] proposed an engineering method for designing

suspended inter-array power cable configurations for offshore wind farms. At present, most studies on the fully suspended configuration of offshore wind farm cables rely on commercial software simulations, while convenient static analysis methods are lacking in the preliminary design stage of cables. Existing convenient analytical methods are suitable for free-suspension cable configurations with one end connected to the platform and the other fixed on the seabed (Trapper; Chen et al.) [19]–[21], but they cannot adapt to fully suspended cable configurations where both ends are connected to platforms.

This study proposes a rapid and straightforward static analysis method for fully suspended inter-array cables in the design phase of offshore wind farms. This method treats the entire cable as a set of multiple individual continuous segments, establishes the cable equilibrium equations based on the principle of minimum potential energy, and obtains the numerical solution through two iterative steps. In the first step, a cable model with a free-hanging configuration is established. In the second step, buoyancy is applied to the cable. In both steps, within each increment, a new equilibrium configuration is obtained by directly minimizing the total potential energy discretized into a Riemann sum. This process generates a system of nonlinear finite difference equations, which are further solved using the Newton-Raphson iterative technique.

Compared with commercial software such as OrcaFlex, the analytical method proposed in this paper delivers superior convenience and efficiency for preliminary design. Parametric analysis in OrcaFlex entails cumbersome modeling and meshing procedures, which are highly time-intensive. By contrast, the present method relies on explicit formulas. Instant results are available merely with basic parameter entry, free from elaborate software operations, and facilitate rapid scheme selection and parameter optimization in the conceptual design phase.

The model proposed in this paper is subject to the following assumptions and limitations. Given the distribution of in-plane loads and the restraint imposed by the mooring system on out-of-plane platform motion, cable deformation occurs predominantly within a single plane. Consequently, the model is developed for two-dimensional (2D) planar static analysis, where shear deformation as well as axial

elongation and contraction are neglected. A full three-dimensional (3D) simulation can reproduce complete spatial mechanical responses but demands considerable computational resources. This 2D method enables efficient, rapid evaluation during conceptual preliminary design, while comprehensive refined validation can be performed subsequently via dedicated 3D numerical simulations.

The structure of this paper is given below. Section 2 establishes a theoretical model and numerical method for the analysis of fully suspended inter-array cables in offshore wind farms. In Section 3, the discretization and iterative solution of the mechanical model are given in detail. In Section 4, the accuracy of the theoretical model is validated with a comparison of results from OrcaFlex. The parametric analysis is also conducted in this chapter. Finally, the main research outcomes of this paper are summarized in Section 5.

## **2. Mathematical formulation**

Fully suspended cables are commonly used for power and signal transmission in offshore wind farms, as shown in Fig.2. Cables between wind turbine arrays can achieve full suspension relying on the buoyancy of buoys. In this case, the cable is divided into two scenarios. One is the installation location of the buoyancy module, the orange part in Fig.3. An upward force is applied to form an upward arch bend in this section. In practical applications, buoys are used individually, but in this paper, their effect is taken as the average value over the length of the buoyancy section. That is to say, the equivalent wet weight per unit length is adopted. In addition, the effect of buoyancy modules on cable bending stiffness is assumed to be negligible[19]. The other scenario is the section without buoys, the blue part in Fig.3. This section is usually a sag bend. The cable configuration shown in Fig.3 is a W-shaped layout. When buoys are randomly distributed at multiple positions along the cable, cable configurations with different upward arch heights will be exhibited.

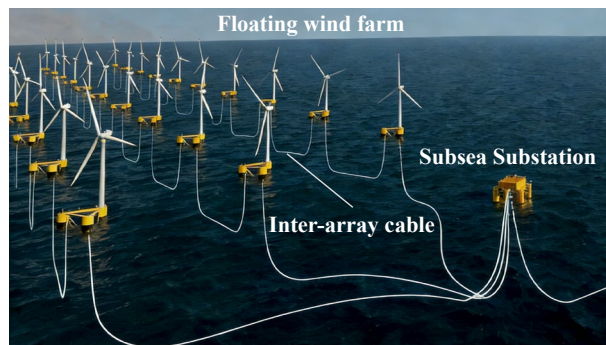


Fig.2 Engineering application of fully suspended cables.

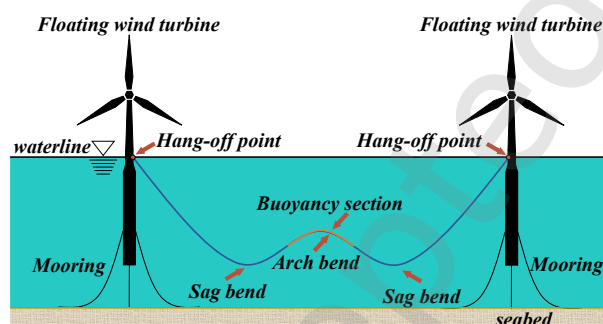


Fig.3 Scheme of the offshore wind turbine cable.

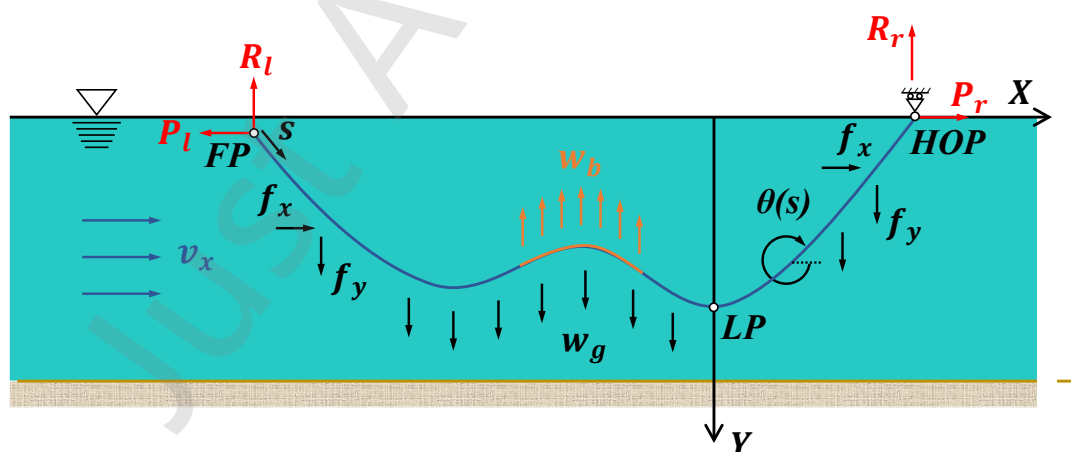


Fig.4 The force diagram of the cables for offshore wind turbines: geometry, gravity, buoyancy, hydrodynamic force, boundary conditions and coordinate systems.

The theoretical model of a fully suspended cable and obtains the distribution of the cable configuration, curvature, bending moment and tension is derived in this section. As shown in Fig.4, an elastic cable of length  $L$  is constrained to deform within a plane and is fully suspended between two wind turbines. This model is established in

the global coordinate system  $XY$  where the  $X$ -axis points along the sea surface toward the right wind turbine and the  $Y$ -axis passes through the lowest point ( $LP$ ) of the cable and extends downward to the seabed. The origin is set at the intersection of the  $X$ -axis and  $Y$ -axis. The cable is subjected to underwater self-weight  $w_g$  distributed along its entire length, buoyancy load  $w_b$  distributed along the length of the buoyant segment  $L_b$ , hydrodynamic loads  $f_x$  and  $f_y$  distributed in the  $x$  and  $y$  directions respectively due to ocean currents with a velocity of  $v_x$ , horizontal top loads  $P_l$  and  $P_r$  exerted by the wind turbines on both sides and vertical tension  $R_l$  and  $R_r$  applied by the wind turbine at the tops of the left and right ends of the cable. The cable configuration is defined by  $\theta(s)$  where  $s$  is the arc length measured from a free point ( $FP$ ) within the plane  $0 \leq s \leq L$ . The coordinate position of the cable is given by Cartesian coordinates  $x$  and  $y$ , as shown below.

$$y(s) = - \int_s^L \sin \theta(s) ds \quad (1)$$

$$x(s) = - \int_0^{s_{LP}} \cos \theta(s) ds + \int_0^s \cos \theta(s) ds \quad (2)$$

The geometric boundary conditions for the above configuration are as follows since the  $Y$ -axis of the coordinate system passes through point  $LP$  it is known that:

$$x(s_{LP}) = 0 \quad (3)$$

At point  $HOP$ , the cable is connected to the wind turbine through a hinge, meaning it is restricted in the  $y$ -direction while being able to rotate and move freely in the  $x$ -direction.

$$y(L) = 0 \quad (4)$$

By controlling  $P_l$  and  $R_l$ , the  $FP$  point of the cable is maintained at the desired  $xy$  coordinate position, rather than specifying the exact location directly.

Based on the coordinate system and boundary conditions proposed above, equations with only angles as unknowns are derived using the principle of minimum

total potential energy, enabling the solution of spatial distributions of cable configuration, curvature, bending moment and tension. This method reasonably employs the core of the principle of minimum total potential energy that the state of minimum total potential energy of the cable system corresponds to the equilibrium state of the cable configuration. When calculating the potential energy, the applied loads and boundary conditions are naturally taken into account, and the resulting mathematical expressions are relatively simple, with all solvable equations being of lower order. Once the unknown quantity  $\theta(s)$  is determined and it is known that  $\theta(s)$  lies in the first quadrant and the fourth quadrant, the configuration of the cable can be calculated. The position of each point is given by coordinates  $x$  and  $y$  as shown in the following equations.

Remarkably, Equations (1) and (2) inherently satisfy boundary conditions (3) and (4) by their fundamental formulation. This coordinate system constitutes the most natural framework for representing the cable's geometry, wherein boundary constraints (3) and (4) are automatically embedded. Alternative coordinate systems may not only compromise simulation accuracy but also necessitate more elaborate methodologies to enforce these boundary conditions.

Once the unknown quantity  $\theta(s)$  is determined, curvature, bending moment and tension can also be calculated using the usual differential relationships.

$$\kappa(s) = d\theta(s)/ds \quad (5)$$

$$M(s) = EI\kappa(s) \quad (6)$$

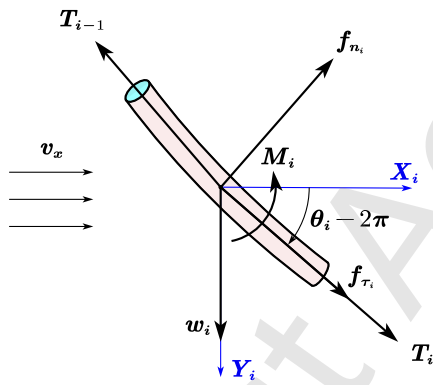
$$\frac{dT(s)}{ds} = f_x \cos\theta(s) - (f_y + w(s)) \sin\theta(s) \quad (7)$$

For Equations (5)-(7),  $ds$  denotes the length of an infinitesimal cable segment with units of  $m$ ;  $d\theta(s)$  is the angle increment of the corresponding infinitesimal cable segment in  $rad$ ;  $\kappa(s)$  represents the curvature of the infinitesimal cable segment with units of  $m^{-1}$ ;  $M(s)$  stands for the bending moment of the infinitesimal cable

segment in  $N \cdot m$ ;  $dT(s)$  refers to the axial tension of the infinitesimal cable segment in  $N$ ;  $f_x$  and  $f_y$  are the x-direction and y-direction components of the ocean current load acting on the infinitesimal cable segment, respectively, with units of  $N$ ; and  $w(s)$  is the generalized gravitational load on the infinitesimal cable segment with units of  $N$ .

The total potential energy of the cable consists of two parts, elastic strain energy and the potential energy of applied forces. An arbitrary element is selected from the middle section of the cable as illustrated in Fig.4. A force analysis diagram of the cable micro-element  $ds_i$  is plotted as shown in Fig.5, based on which the total potential energy of the cable is calculated.

*Cable micro – element  $ds_i$ : if  $\sin\theta_i > 0$*



*Cable micro – element  $ds_i$ : if  $\sin\theta_i < 0$*

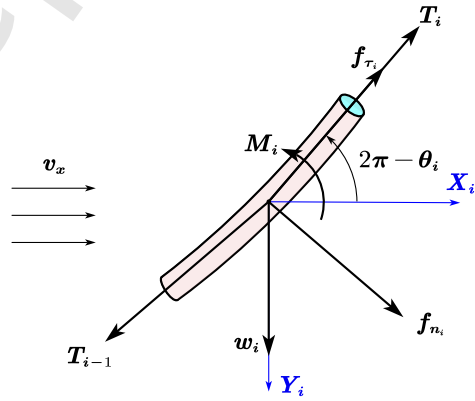


Fig.5 Force analysis diagram of cable micro-element  $ds_i$

Elastic strain energy  $U_e$  is the energy generated by the bending of the cable itself as shown in the following equations.

$$U_e = \frac{1}{2} \int_L EI \kappa(s)^2 ds \quad (8)$$

Here,  $E$  is the equivalent Young's modulus of the cable,  $I$  is the moment of inertia of the cable cross-section, and  $\kappa$  is its planar curvature.

The applied forces include gravity, buoyancy, horizontal tension at the left end of the cable, vertical tension at the left end of the cable, horizontal tension at the right end of the cable, vertical tension at the right end of the cable, and ocean current forces.

Gravity  $w_g$  and buoyancy  $w_b$  of the cable are completely opposite vectors and can be combined into the generalized gravity  $w(s)$  of the cable, leading to the potential energy  $U_w$  of the generalized gravity as shown in the following equations.

$$w(s) = w_g + \begin{cases} w_b, & s \in L_b \\ 0, & s \notin L_b \end{cases} \quad (9)$$

$$U_w = \int_L w_g y(s) ds + \int_{L_b} w_b y(s) ds \quad (10)$$

To account for the hydrodynamic loads generated by a steady ocean current with a velocity of  $v_x$ , the drag forces exerted by the current on the cable are calculated using the Morison equation. These forces in the normal and tangential directions are given as follows:

$$f_n = \begin{cases} \frac{1}{2} \rho_w C_n D |v_x(y) \sin \theta| v_x(y) \sin \theta, & \sin \theta > 0 \\ -\frac{1}{2} \rho_w C_n D |v_x(y) \sin \theta| v_x(y) \sin \theta, & \sin \theta < 0 \end{cases} \quad (11)$$

$$f_\tau = \frac{1}{2} \rho_w C_\tau \pi D |v_x(y) \cos \theta| v_x(y) \cos \theta \quad (12)$$

Here,  $D$  represents the outer diameter of the pipeline, while  $C_n$  and  $C_\tau$  denote the normal and tangential drag coefficients, respectively. Decomposing these forces into the x- and y-directions yields:

$$f_x = f_\tau \cos \theta + \begin{cases} f_n \sin \theta, & \sin \theta > 0 \\ -f_n \sin \theta, & \sin \theta < 0 \end{cases} \quad (13)$$

$$f_y = f_\tau \sin \theta + \begin{cases} f_n \cos \theta, & \sin \theta < 0 \\ -f_n \cos \theta, & \sin \theta > 0 \end{cases} \quad (14)$$

Therefore, the potential energy generated by the ocean current forces in the x and y directions is as shown in the following equations.

$$U_c = \int_L f_x x(s) ds + \int_L f_y y(s) ds \quad (15)$$

The potential energies generated by the horizontal tension at the left end of the cable, the horizontal tension at the right end of the cable, the vertical tension at the left

end of the cable, and the vertical tension at the right end of the cable are  $P_l x(0)$ ,  $P_r x(L)$ ,  $R_l y(0)$ , and  $R_l y(L)$  respectively. According to the boundary conditions (4),  $R_l y(L)$  in the vertical direction is zero. Based on the force analysis, there is a relationship of Eq. (16) in the horizontal direction. Therefore, the potential energy  $U_p$  of the horizontal tensions and the potential energy  $U_r$  of the vertical tensions can be obtained as shown in the following equations.

$$P_l = P_r + \int_L f_x ds \quad (16)$$

$$U_p = P_l x(0) + P_r x(L) \quad (17)$$

$$U_r = R_l y(0) \quad (18)$$

Based on the above analysis, the total potential energy of the fully suspended cable in Fig.4 is given by the following equation.

$$U_{tot} = \frac{1}{2} \int_L EI \kappa(s)^2 ds - \int_L w_g y(s) ds - \int_{L_b} w_b y(s) ds - \int_L f_x x(s) ds - \int_L f_y y(s) ds - P_l x(0) - P_r x(L) - R_l y(0) \quad (19)$$

Observing the above, it can be found that compared with previous studies[19], this study converts the left fixed point of the cable into an *FP*, introduces the *FP* control load potential energy terms  $P_l x(0)$  and  $R_l y(0)$ , as well as the equilibrium relationship between  $P_l$  and  $P_r$ , and considers the differences in the angle between the current and the cable in different quadrants for  $f_x$  and  $f_y$  in the current load potential energy term. Therefore, this study has the advantages of *FP* control for inter-array cables and accurate solution of current loads.

### 3. Numerical implementation

The total potential energy of the cable is expressed as a Riemann sum in terms of the discrete variables  $\theta_i$ , as follows:

$$U_{tot} = \Delta s \sum_{i=1}^N \frac{1}{2} EI \left( \frac{\theta_{i+1} - \theta_i}{\Delta s} \right)^2 - \sum_{i=1}^{N+1} w_i y_i - \sum_{i=1}^{N+1} f_x^i x_i - \sum_{i=1}^{N+1} f_y^i y_i - P_l x_1 - P_r x_{N+1} - R_l y_1^* \quad (20)$$

The generalized gravitational load at each nodal point of the cable is given by:

$$w_i = w(s) \Delta s \quad (21)$$

The hydrodynamic load at each nodal point is given by:

$$f_x^i = f_\tau^i \cos \theta_i + \begin{cases} f_n^i \sin \theta_i, & \sin \theta_i > 0 \\ -f_n^i \sin \theta_i, & \sin \theta_i < 0 \end{cases} \quad (22)$$

$$f_y^i = f_\tau^i \sin \theta_i + \begin{cases} f_n^i \cos \theta_i, & \sin \theta_i < 0 \\ -f_n^i \cos \theta_i, & \sin \theta_i > 0 \end{cases} \quad (23)$$

Equations (21) and (22) are derived from Equations (23) and (24):

$$f_n^i = \begin{cases} \frac{1}{2} \rho_w C_n D |v_x^i \sin \theta_i| v_x^i \sin \theta_i, & \sin \theta_i > 0 \\ -\frac{1}{2} \rho_w C_n D |v_x^i \sin \theta_i| v_x^i \sin \theta_i, & \sin \theta_i < 0 \end{cases} \quad (24)$$

$$f_\tau^i = \frac{1}{2} \rho_w C_\tau \pi D |v_x^i \cos \theta_i| v_x^i \cos \theta_i \quad (25)$$

The horizontal load relationship between the two ends of the cable is expressed by Equation (25).

$$P_l = P_r + \sum_{i=1}^{N+1} f_x^i \quad (26)$$

The discretized coordinate values in the cable configuration calculation are given as follows:

$$x_i = \sum_{j=1}^{i-1} \cos \theta_j \Delta s - \sum_{j=1}^{i_D-1} \cos \theta_j \Delta s \quad (27)$$

$$y_i = \begin{cases} \sum_{j=1}^{i-1} \sin \theta_j \Delta s, & i \leq i_{LP} \\ -\sum_{j=i}^N \sin \theta_j \Delta s, & i > i_{LP} \end{cases} \quad (28)$$

$$y_i^* = -\sum_{j=i}^N \sin \theta_j \Delta s \quad (29)$$

In the static analysis, the extremum (minimum) of the total potential energy function  $U_{tot}$  with respect to the discrete variables  $(\theta_1, \dots, \theta_{N+1})$  is sought to obtain the appropriate cable configuration under static equilibrium conditions.

$$\frac{\partial U_{tot}(\theta_1, \dots, \theta_{N+1})}{\partial \theta_i} = 0, \quad i = 1, \dots, N+1 \quad (30)$$

The total potential energy function  $U_{tot}$  with respect to each discrete variable  $(\theta_1, \dots, \theta_{N+1})$  and set the derivatives to zero is derived, yielding a nonlinear system of  $(N+1)$  equations. This system contains the same number of equations as discrete variables, and since its matrix is non-singular, the discrete variables must admit a unique solution set.

$$\left\{ \begin{array}{l} \frac{EI}{\Delta s}(\theta_{i-1} - 2\theta_i + \theta_{i+1}) - \sum_{j=i}^{i_D-1} (w + f_y^j) \Delta s \cos \theta_i - \sum_{j=i}^{i_D-1} f_x^j \Delta s \sin \theta_i - P_l(-\Delta s \sin \theta_i) - R_l(-\Delta s \cos \theta_i) = 0 \\ \quad i = 1, \dots, i_{LP} \\ \frac{EI}{\Delta s}(-\theta_{i-1} + 2\theta_i - \theta_{i+1}) - \sum_{j=i_D+1}^i (w + f_y^j) \Delta s \cos \theta_i - \sum_{j=i}^{N+1} f_x^j \Delta s \sin \theta_i - P_r(-\Delta s \sin \theta_i) - R_r(-\Delta s \cos \theta_i) = 0 \\ \quad i = i_{LP} + 1, \dots, N+1 \end{array} \right. \quad (31)$$

The nonlinear system of equations is solved using the Newton-Raphson method. An initial set of estimated values is first determined, and in each iteration, progressively more accurate approximations are computed. The computational process terminates once the difference between successive approximations falls within the permissible error tolerance. The procedure begins by establishing an initial U-shaped catenary of length  $L$ . Taking an infinitesimal segment  $\Delta s$ , the number of unknown variables  $\theta_i$  is determined. Based on  $w_g$  and  $P_r$ , the initial configuration is defined, and iterative solving at this length yields the new static equilibrium and updated configuration.

$$\theta_i^{(0)} = 2\pi - \arctan\left(\frac{w_g}{P_r}\left(i - \frac{N}{2} - 1\right)\Delta s\right) \quad (32)$$

The second step involves determining the static equilibrium configuration of the cable under buoyant forces. During this phase, the total cable length is held constant while progressively updating the generalized gravitational load  $w(s)$ . This is achieved

by systematically applying incremental uplift forces to the nodes within the buoyancy-influenced segment  $L_b$ , enabling iterative refinement of the equilibrium solution. The iterative procedure proceeds as follows:

$$w_i^k = w_i^{k-1} + \Delta w_b \quad (33)$$

$$\theta^{(N+1,n)} = \theta^{(N+1,n-1)} + \Delta \theta^{(N+1,n)} \quad (34)$$

At each iteration, the solution from the previous step  $\theta^{(N+1)}$  serves as the initial estimate  $\theta^{(N+1,n-1)}$  for the subsequent calculation. The iterative procedure continues until the incremental change  $\Delta \theta^{(N+1,n)}$  satisfies the predefined convergence criteria, at which point the process terminates. The overall calculation flowchart is presented in Fig.6.

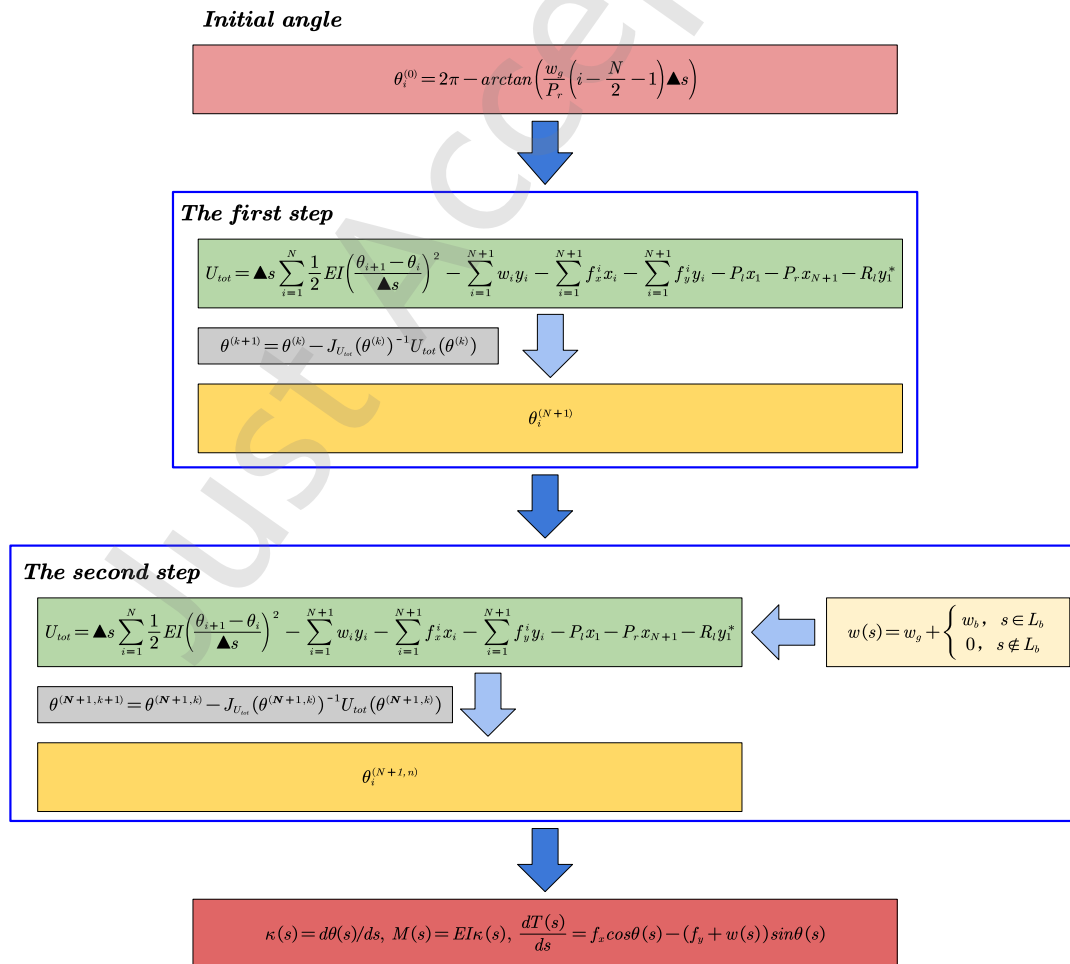


Fig.6 Calculate flowchart.

## 4. Validation and parameter analysis

### 4.1 Model validation

To verify the accuracy of the current mathematical model, the theoretical results are compared with those from OrcaFlex (the numerical modeling method follows the study by Ahmad I B et al.[22]) in terms of cable configuration, curvature, bending moment, and axial tension, respectively. During the verification process, the span between the platforms is 1199 m, and the total length of the cable is 1240 m. To test the suitability of the model for subsequent parametric analysis, the buoy arrangement is referenced from the work of Ahmad I B et al. [22]. Four buoy segments are installed to form a multi-W-configuration of the cable. Each buoy segment is 10 m long, starting at longitudinal positions of 300 m, 500 m, 700 m and 900 m. A 10-year return period current profile is adopted for the ocean current, as shown in Fig.7[20].

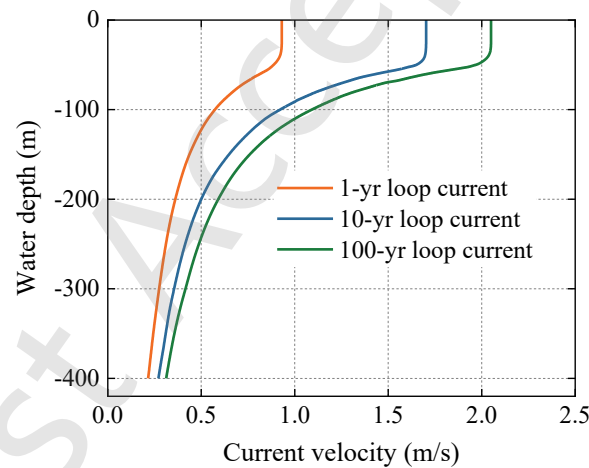


Fig.7 Current profile.

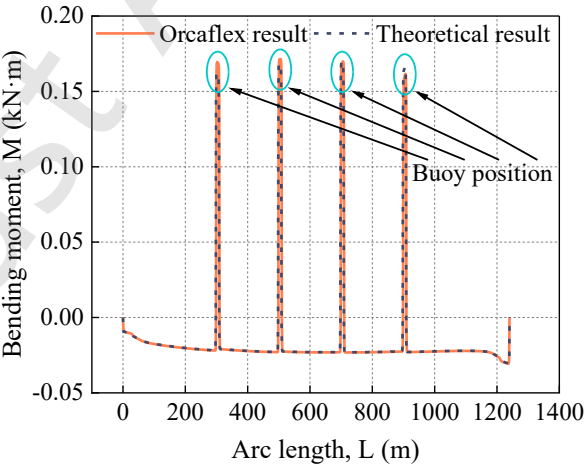
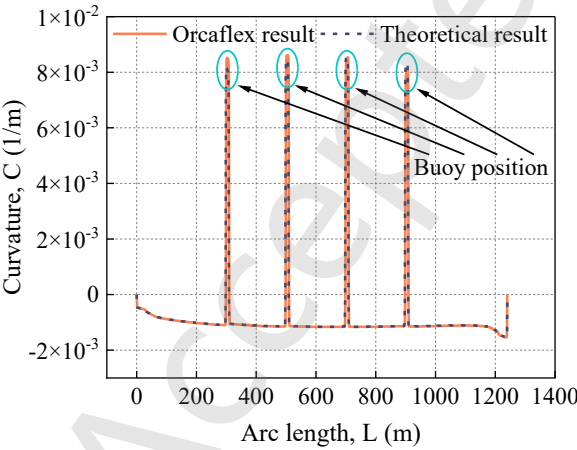
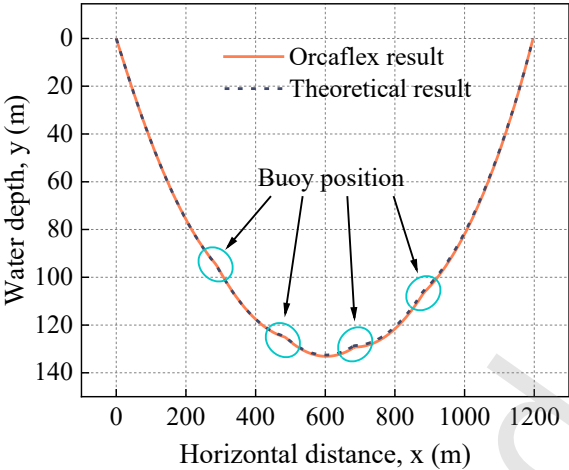
In this paper, the cable parameters are referenced from Lozon et al.[23], including the cable diameter ( $D$ ), bending stiffness ( $EI$ ), linear mass density ( $w_g/g$ ), minimum breaking load ( $MBL$ ), and maximum allowable curvature ( $MAC$ ). In addition, Table 1 includes the outer diameter of the buoyancy module ( $D_b$ ), the density of the buoyancy module ( $\rho_b$ ), seawater density ( $\rho_w$ ), the normal drag coefficient ( $C_n$ ), and the tangential drag coefficient ( $C_\tau$ ). Of particular importance, the effective weight per unit

length of the buoyancy module is calculated as  $w_b = (\rho_b - \rho_w)gA_b$ , where  $A_b$  represents the cross-sectional area of the buoyancy module, which is derived from the geometric relation  $A_b = \pi(D_b^2 - D^2)/4$ .

Table 1 Basic parameters.

| Parameter                             | Symbol     | Value  |
|---------------------------------------|------------|--------|
| Cable diameter [ $m$ ]                | $D$        | 0.16   |
| Linear mass density [ $kg/m$ ]        | $w_g/g$    | 36.7   |
| Bending stiffness [ $kN \cdot m^2$ ]  | $EI$       | 19.9   |
| Minimum Breaking Load [ $kN$ ]        | $MBL$      | 383    |
| Maximum Allowable Curvature [ $1/m$ ] | $MAC$      | 0.4149 |
| Seawater density [ $kg/m^3$ ]         | $\rho_w$   | 1030   |
| Buoyancy module diameter [ $m$ ]      | $D_b$      | 0.618  |
| Buoyancy module density [ $kg/m^3$ ]  | $\rho_b$   | 583    |
| Normal drag coefficient               | $C_n$      | 1.2    |
| Tangential drag coefficient           | $C_\tau$   | 0.024  |
| Acceleration of gravity [ $m/s^2$ ]   | $g$        | 9.8    |
| Microelement length [ $m$ ]           | $\Delta s$ | 1      |

To facilitate result observation, all subsequent results undergo a simple translation transformation of the coordinate system  $Y$ -axis, shifting it to the leftmost end of the cable. As shown in Fig.8(a) to (d), comparative diagrams of the wind farm cable configuration, curvature, bending moment, and axial tension results are presented. It can be observed that the theoretical results and OrcaFlex results show good consistency in terms of cable configuration and axial tension in space, while minor errors exist in cable curvature and bending moment at the positions where buoys are applied.



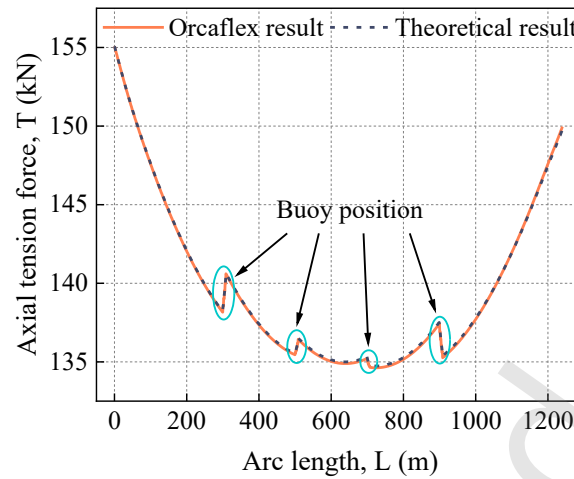


Fig.8 Validation and comparison of theoretical result and Orcaflex result. (a) Configuration; (b) Curvature; (c) Bending moment; (d) Axial tension force.

As shown in Table 2, the maximum water depth, maximum axial tension, maximum bending moment and maximum curvature of the wind farm cable are very close. The maximum error between the theoretical method and OrcaFlex simulation is less than 1%, and the root mean square error of the theoretical method relative to the OrcaFlex simulation is small. This reflects the accuracy of the theoretical method and proves that the method can be used to simulate fully suspended inter-array cables.

Table 2 Comparison of theoretical results with Orcaflex results and error analysis.

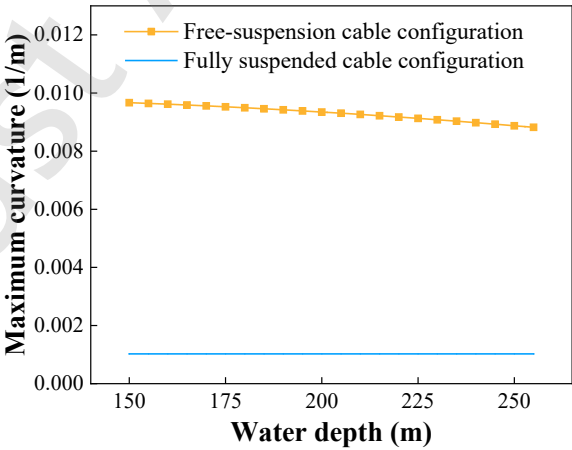
| Item                        | $y$       | $T$        | $M$          | $C$                      |
|-----------------------------|-----------|------------|--------------|--------------------------|
| Maximum theoretical results | 132.5626m | 155.2889kN | 0.1698kN • m | 0.0085m <sup>-1</sup>    |
| Maximum Orcaflex result     | 133.0985m | 155.0789kN | 0.1714kN • m | 0.0086m <sup>-1</sup>    |
| Maximum error (%)           | 0.40      | -0.14      | 0.96         | 0.93                     |
| Root Mean Square Error      | 0.4895m   | 0.0829kN   | 0.0123kN • m | 6.1856e-4m <sup>-1</sup> |

## 4.2 Comparison between fully suspended cable configuration and free-suspension cable configuration

Offshore wind power cable design is usually a repeated iterative process. Each design stage is interrelated, and the results of the previous stage directly constrain the subsequent scheme, ultimately aiming to achieve the optimal life-cycle cost[24]-[25]. From three aspects including the static analysis in the preliminary design of cables, power transmission and installation mode, this subsection carries out a simple comparative analysis and discussion on the two cable configurations shown in Fig.1. Both configurations have a total cable length of 1240m and are not equipped with buoys. The ocean current adopts the 10-year return period current profile as shown in Fig.7. The cable parameters are given in Table 1. The parameter settings are listed in Table 3.

Table 3 Parameter variable.

| Item                      | Water depth                                             | Horizontal span                                  |
|---------------------------|---------------------------------------------------------|--------------------------------------------------|
| Effect of water depth     | $\{W_d m   W_d = 150 + 5i, i \in Z, 0 \leq i \leq 21\}$ | 1199m                                            |
| Effect of horizontal span | 215m                                                    | $\{H_s m   1180 \leq H_s \leq 1209, H_s \in Z\}$ |



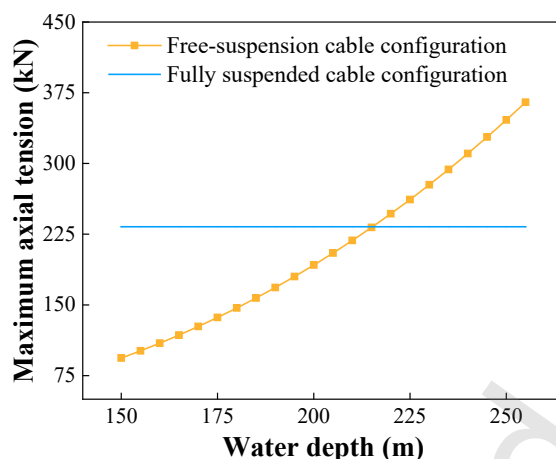


Fig.9 Effect of water depth on the fully suspended cable configuration and the free-suspension cable configuration. (a) Maximum curvature; (b) Maximum axial tension.

As shown in Fig.9, the increase in water depth has no effect on the maximum axial tension and maximum curvature of the fully suspended cable configuration, but has a significant effect on those of the free-suspension cable configuration. As shown in Fig.9(a), the bending degree of the free-suspension cable configuration is greater than that of the fully suspended cable configuration, and the maximum curvature of the former is approximately 9 times that of the latter. As shown in Fig.9(b), the maximum axial tension of the free-suspension cable is more significantly affected by water depth. When the water depth is less than 215 m, the maximum axial tension of the free-suspension cable configuration is smaller than that of the fully suspended cable configuration. For the former configuration, part of the cable is laid on the seabed and is only subjected to the gravity load of the suspended segment, while the cable of the latter configuration is subjected to the full gravity load. With the increase in water depth, the length of the suspended segment of the free-suspension cable increases, leading to an increase in gravity and thus an increase in the maximum axial tension. When the water depth exceeds 215 m, the maximum axial tension of the free-suspension cable becomes greater than that of the fully suspended cable configuration.

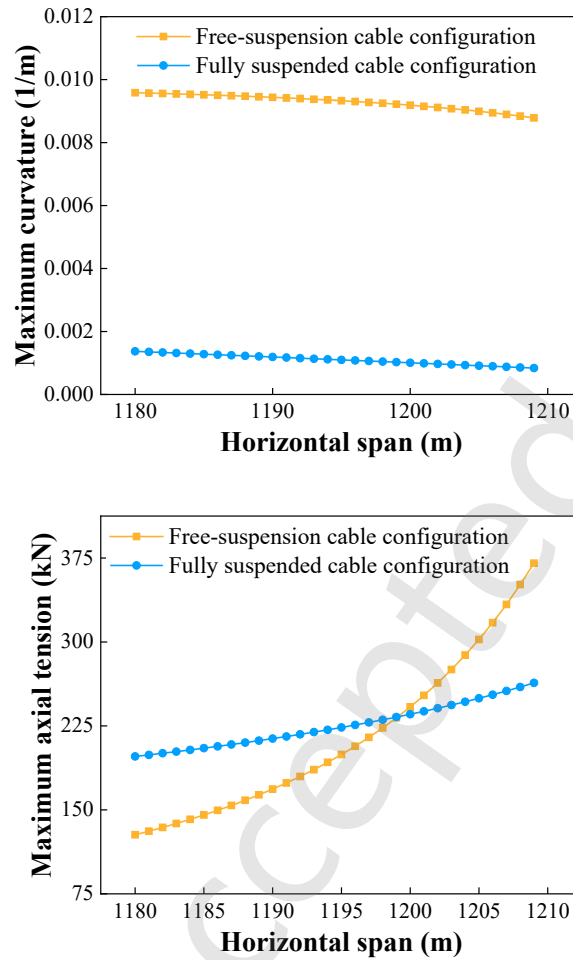


Fig.10 Effect of horizontal span on the fully suspended cable configuration and the free-suspension cable configuration. (a) Maximum curvature; (b) Maximum axial tension.

As shown in Fig.10, the increase in horizontal spacing affects both cable configurations. As shown in Fig.10(a), when the horizontal span increases from 1180 m to 1209 m, the maximum curvature of the free-suspension cable configuration decreases by 8.34%, and that of the fully suspended cable configuration decreases by 38.73%. The bending degree of the free-suspension cable configuration is greater than that of the fully suspended cable configuration, with the maximum curvature of the former being more than 7 times that of the latter. As shown in Fig.10, when the horizontal span increases from 1180 m to 1209 m, the maximum axial tension of the free-suspension cable configuration increases by 189.95%, and that of the fully suspended cable configuration increases by 33.25%. The maximum axial tension of the free-suspension cable is affected more significantly by the horizontal span.

In a wind farm power transmission, the free-suspension configuration transmits the electric energy of each wind turbine individually to the subsea substation. It is vulnerable to spatial layout limitations and requires longer cables. As water depth increases continuously, the free-suspension configuration not only faces an increase in maximum axial tension but also generates significant energy loss due to long-distance transmission. Meanwhile, the increase in cable length leads to higher economic costs. The fully suspended configuration collects the electric energy of wind turbines before transmitting it to the subsea substation. It reduces the cable length from each wind turbine to the substation and features strong layout scalability.

Free-suspension cables usually adopt an S-type or J-type laying and installation. They involve complex processes such as laying route inspection, underwater information transmission and subsea cable burial. Meanwhile, the laying length and complex installation terrain prolong the offshore construction period and incur high costs. Fully suspended cables adopt an installation method where one end is connected to the wind turbine platform and the other end is connected in place by positioning and towing. The installation equipment is simple, unaffected by seabed terrain, and the offshore construction period is short.

### **4.3 Analysis of Cable Layout Plans under Different Conditions**

In the parameter analysis of wind farm cables, the basic parameters are provided in Table 1, and only one specific parameter is changed in each simulation. The specific parameters considered include buoy length, buoy arrangement and ocean current velocity. It is worth noting that the buoy length herein represents the total length of buoy segments instead of the length of an individual buoy, with each single buoy set to 1 m in this study. These specific parameters have a significant impact on the axial tension and curvature of the cable. Analyzing the influence of specific parameters on the axial tension and curvature of the cable can provide guidance for cable design.

#### **4.3.1 The influence of buoy length on mechanical response**

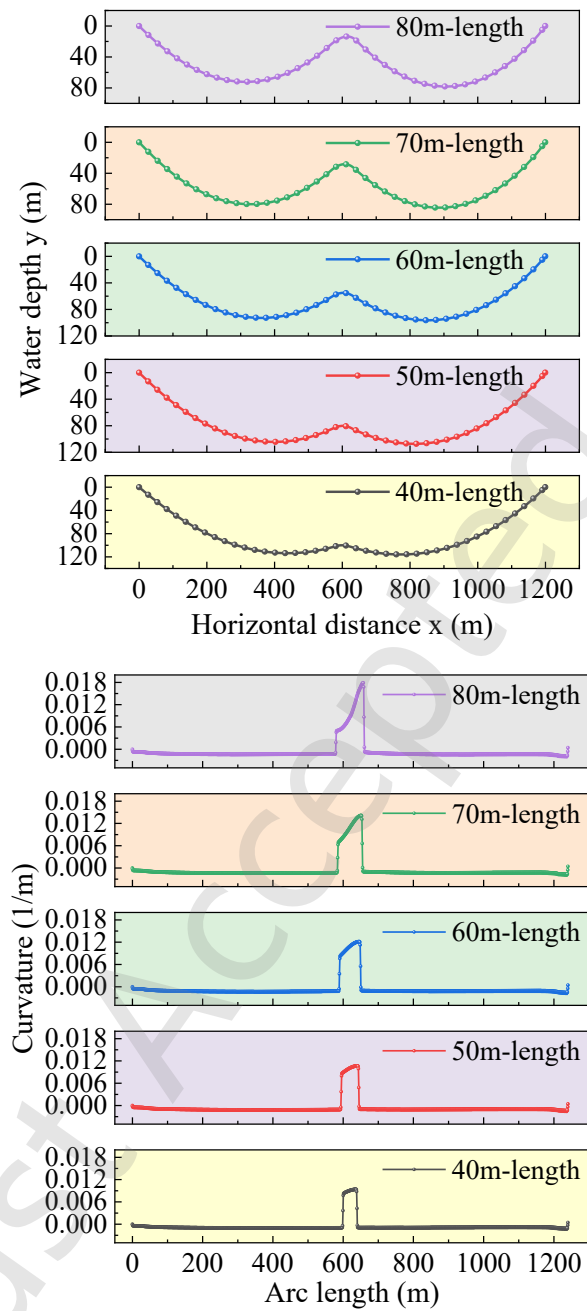
Changes in buoy length have a significant impact on the axial tension and curvature of the cable. The span between the platforms equals 1199 m, and the total cable length is 1240 m. The ocean current adopts the 10-year return period current

profile as shown in Fig.7. Only one section of buoys is arranged at the midpoint of the cable[17]. The buoy length increases from 40 m to 80 m at an interval of 10 m. The buoy placement is shown in Table 4.

Table 4 Buoy Layout Plan 1

| Configuration | Buoy Placement Range |
|---------------|----------------------|
| 40m-length    | 600m-639m            |
| 50m-length    | 595m-644m            |
| 60m-length    | 590m-649m            |
| 70m-length    | 585m-654m            |
| 80m-length    | 580m-659m            |

Fig.11(a) illustrates the variation in cable configuration across different buoy lengths. Fig.11(b) and (c) depict curvature and axial tension distributions along the cable. As buoy length increases, the maximum curvature rises from  $9.17 \times 10^{-3} \text{ m}^{-1}$  to  $1.77 \times 10^{-2} \text{ m}^{-1}$ , marking a 92.69% increase. The relative changes in maximum curvature are as follows: 13.89%, 14.15%, 16.67%, 27.05%. Conversely, maximum axial tension decreases from 152.01kN to 119.74kN, reflecting a 21.23% reduction. The corresponding changes (- indicates reduction) are: -10.01%, -8.30%, -4.79%, 0.25%. Notably, increasing buoy length from 40 m to 70 m reduces axial tension due to enhanced buoyancy. When the buoy length extends to 80 m, excessive buoyancy sharply elevates the arch amplitude of the suspended cable. This pronounced arch deformation enlarges the incident angle between the cable axis and ocean current, raises the total normal hydrodynamic drag, and increases the projected flow area of buoy modules. The growth of hydrodynamic load outweighs the tension-reduction benefit from buoyant weight relief, thereby causing a rebound in maximum axial tension.



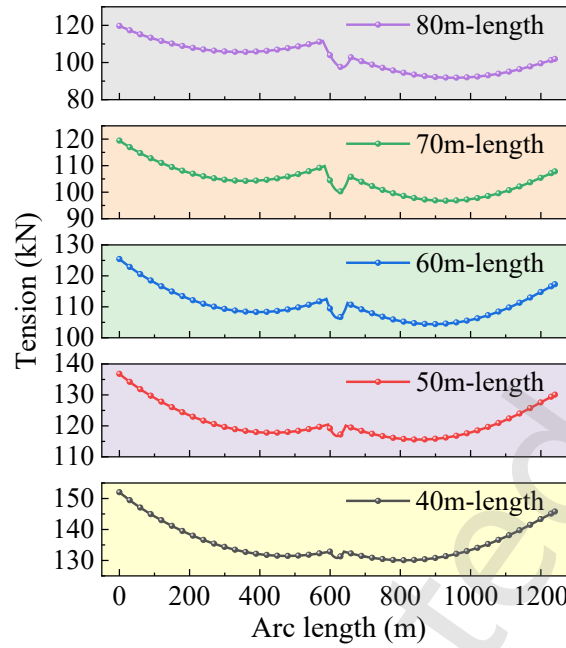


Fig.11 (a) Configuration; (b) Curvature; (c) Axial tension force.

#### 4.3.2 The influence of buoy position on the mechanical response

Buoy positions exert a significant influence on the axial tension and curvature of the cable. In this section, the effects of varying buoy spacing[22] and the number of buoy groups[17] on the mechanical properties of the cable are analyzed, providing mechanical recommendations for cable design.

The span between the platforms is 1199 m, and the total cable length is 1240 m. The ocean current adopts the 10-year return period current profile as shown in Fig.7. The total length of the buoys is 80 m, with ten sections arranged equidistantly on both sides starting from the midpoint of the cable. The spacing between buoys increases from 30 m to 70 m at an interval of 10 m. The buoy placement is shown in Table 5.

Table 5 Buoy Layout Plan 2

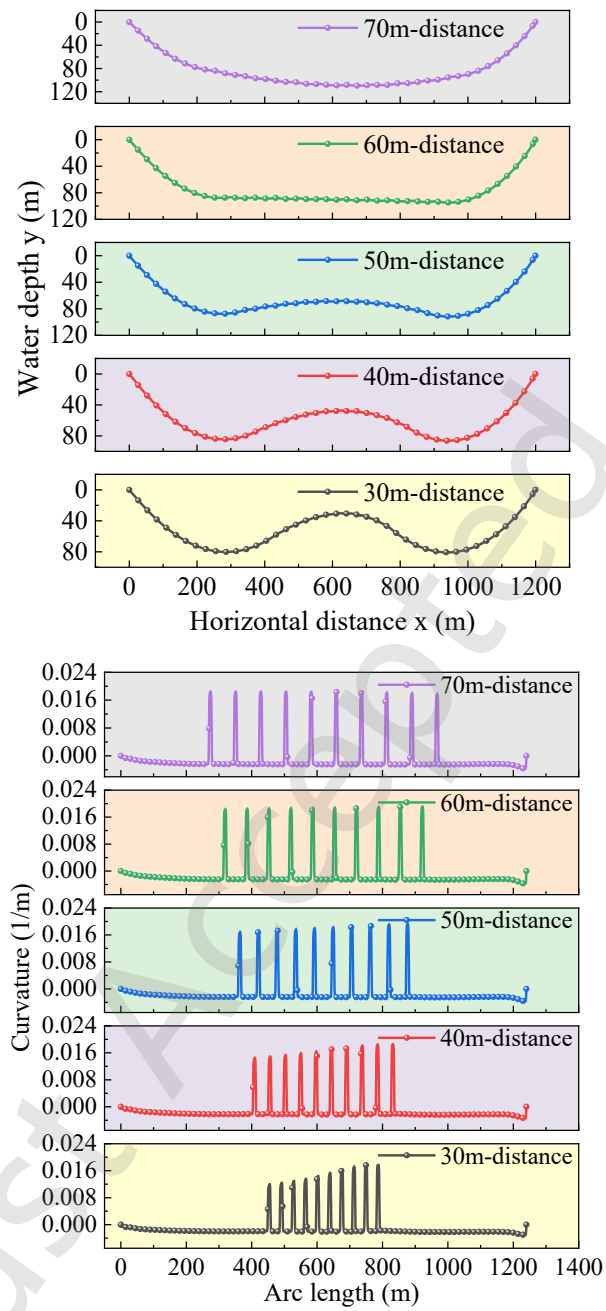
| Configuration | Buoy layout rule                                                   |
|---------------|--------------------------------------------------------------------|
| 30m-distance  | $[620 \pm (37i - 22)]m - [620 \pm (37i - 15)]m, i = 1, 2, 3, 4, 5$ |
| 40m-distance  | $[620 \pm (37i - 17)]m - [620 \pm (37i - 10)]m, i = 1, 2, 3, 4, 5$ |
| 50m-distance  | $[620 \pm (37i - 12)]m - [620 \pm (37i - 5)]m, i = 1, 2, 3, 4, 5$  |
| 60m-distance  | $[620 \pm (37i - 7)]m - [620 \pm 37i]m, i = 1, 2, 3, 4, 5$         |

$$70\text{m-distance} \quad [620 \pm (37i - 2)]m - [620 \pm (37i + 5)]m, i = 1, 2, 3, 4, 5$$

As demonstrated in Fig.12(a), variations in buoy spacing significantly influence the cable configuration. Fig.12(b) and (c) further reveal the corresponding mechanical responses, presenting the curvature distribution and axial tension evolution along the cable span. With increasing buoy spacing, the maximum curvature variations are: +4.62%, +3.77%, -0.57%, -3.35%, and the maximum axial tension changes are: -7.36%, -5.53%, -2.52%, +1.10%. The observed inverse relationship between these two critical parameters indicates that an optimal buoy spacing exists, capable of concurrently mitigating excessive bending and tension.

With the increase in buoy spacing from 30 m to 70 m, the maximum curvatures are  $0.01773 \text{ m}^{-1}$ ,  $0.01855 \text{ m}^{-1}$ ,  $0.01925 \text{ m}^{-1}$ ,  $0.01914 \text{ m}^{-1}$ , and  $0.01846 \text{ m}^{-1}$ , with corresponding ratios to the maximum allowable curvature (MAC) of 4.2733%, 4.4710%, 4.6397%, 4.6132%, and 4.4493%. The maximum axial tensions under each case are 92.8445kN, 86.0154kN, 81.2625kN, 79.2130kN, and 80.0834kN, whose ratios to the minimum breaking load (MBL) are 24.2416%, 22.4583%, 21.2174%, 20.6822%, and 20.9095%. The sum of the two normalized ratios (maximum curvature/MAC + maximum axial tension/MBL) is calculated as 28.5150%, 26.9293%, 25.8570%, 25.2954%, and 25.3588%, respectively.

This composite index quantifies the overall mechanical utilization level of the cable. The total ratio declines continuously as buoy spacing rises from 30 m to 60 m and reaches its minimum value of 25.2954% at a buoy spacing of 60 m. When the buoy spacing further increases to 70 m, the composite index rises slightly. Therefore, the buoy spacing of 60 m is identified as the optimal design value for balancing bending and tension performance under the studied working conditions, and the recommended optimal spacing range is 50 m-70 m.



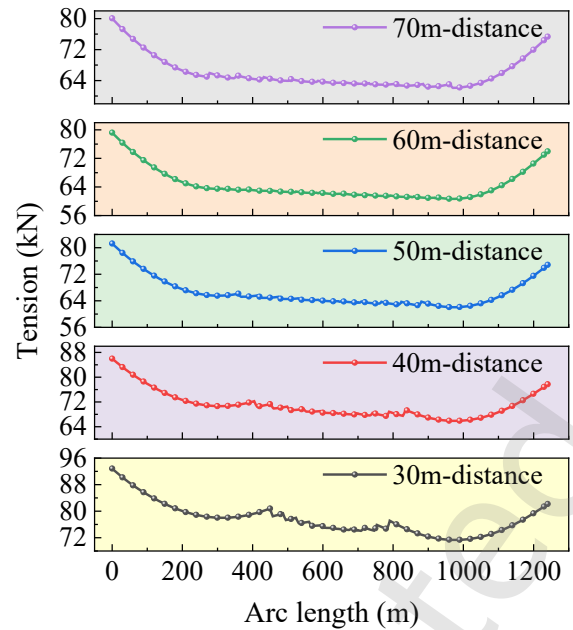


Fig.12 (a) Configuration; (b) Curvature; (c) Axial tension force.

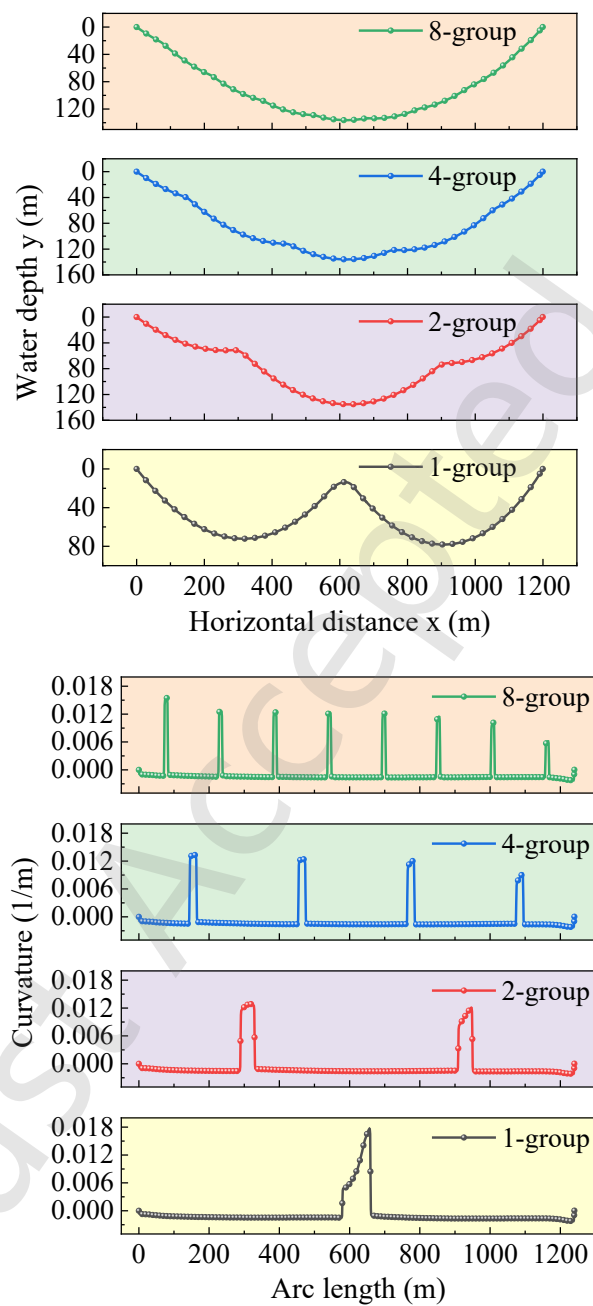
The inter-platform span length measures 1199m with a total cable length of 1240m. The ocean current adopts the 10-year return period current profile as shown in Fig.7. The collective length of buoyancy modules sums to 80 m, distributed symmetrically about the cable midpoint in uniform spacing configurations of 1, 2, 4, and 8 groups. The buoy placement is shown in Table 6.

Table 6 Buoy Layout Plan 3

| Configuration | Buoy Placement Range                                                                        |
|---------------|---------------------------------------------------------------------------------------------|
| 1-group       | 580m-659m                                                                                   |
| 2-group       | 290m-329m、 910m-949m                                                                        |
| 4-group       | 145m-164m、 455m-472m、 765m-784m、 1075m-1094m                                                |
| 8-group       | 73m-82m、 228m-237m、 383m-392m、 538m-547m、<br>693m-702m、 848m-857m、 1003m-1012m、 1158m-1167m |

Fig.13(a) depicts the variations in cable configuration corresponding to different buoy group quantities. Fig.13(b) and (c)present the curvature distribution and axial tension characteristics along the cable length, respectively. As the number of buoy groups increases, the observed variations are as follows: maximum curvature changes by -27.26%, +3.58%, and +16.24%, while maximum axial tension exhibits variations of -7.61%, -0.88%, and -0.48%. The results demonstrate that appropriately distributing

the buoy modules of equal total length along the cable can effectively reduce the mechanical loads on the cable structure.



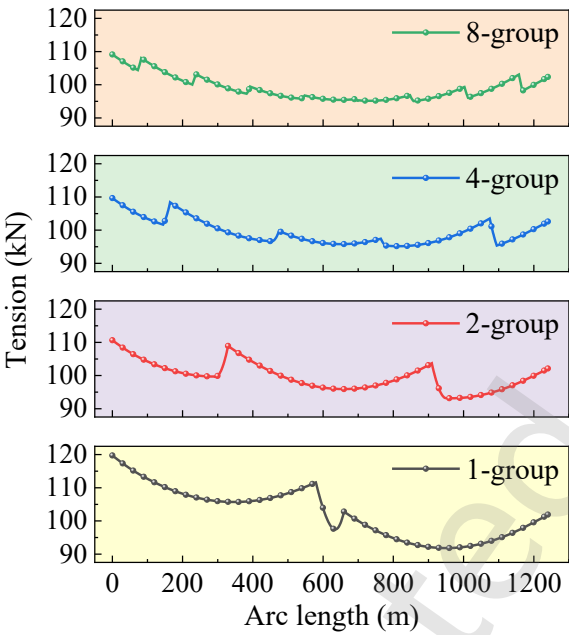


Fig.13 (a) Configuration; (b) Curvature; (c) Axial tension force.

4.3.3 The impact of ocean current load on the mechanical response

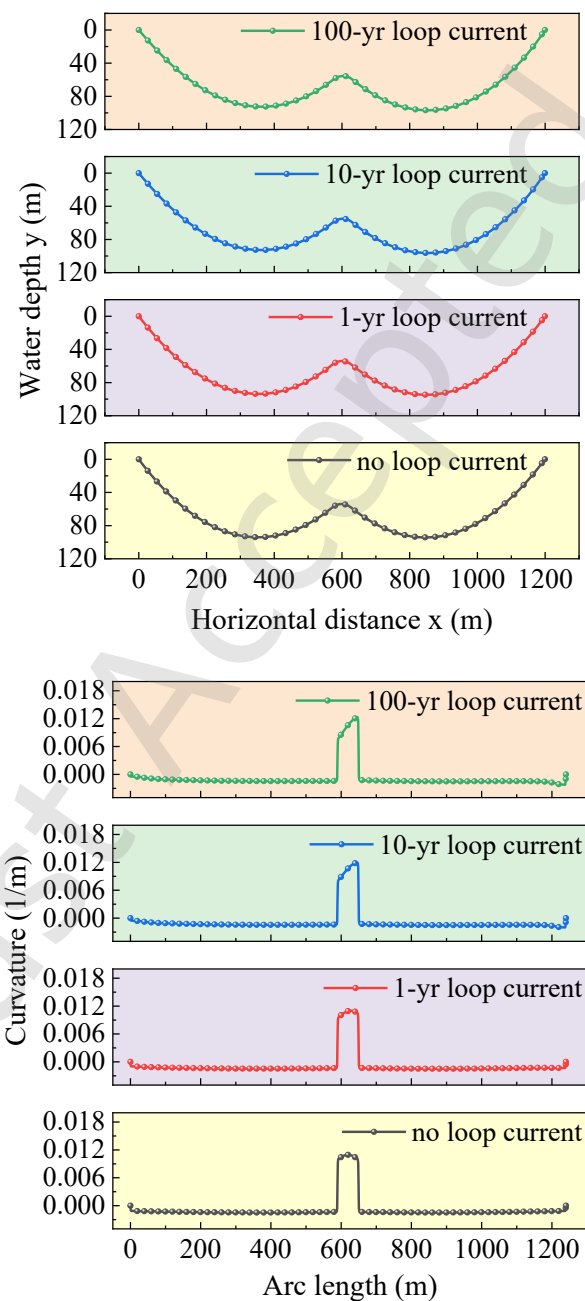
This section analyzes the effect of ocean current velocity on the axial tension and curvature of the cable. The span between the platforms is 1199m, the total length of the cable is 1240m, and the total length of the buoys is 60m. The buoys are arranged at the middle position of the cable, 590m-649m. In Table 7, four working cases are set up, namely the 1-year return period current, the 10-year return period current, the 100-year return period current profile shown in Fig.7, and the no-current condition.

Table 7 Buoy Layout Plan 4

| Configuration       | Buoy Placement Range |
|---------------------|----------------------|
| no loop current     | 590m-649m            |
| 1-yr loop current   |                      |
| 10-yr loop current  |                      |
| 100-yr loop current |                      |

Fig.14(a) demonstrates the evolution of cable profiles under varying oceanic current intensities. Fig.14(b) and (c) present the distribution of curvature and axial tension along the cable length. As the ocean current velocity increases, the maximum curvature increases from  $1.09 \times 10^{-2}m^{-1}$  to  $1.23 \times 10^{-2}m^{-1}$ , representing an increase of 12.26%, with corresponding percentage changes of 0.63%, 8.34%, and

2.93%. Meanwhile, the maximum axial tension rises from 120.62kN to 126.61kN, an increase of 4.97%, with percentage changes of 0.87%, 3.10%, and 0.93% respectively. The increase in current velocity leads to simultaneous growth in both the maximum curvature and maximum axial tension of the cable, both of which exhibit a nonlinear increasing trend with rising flow velocity.



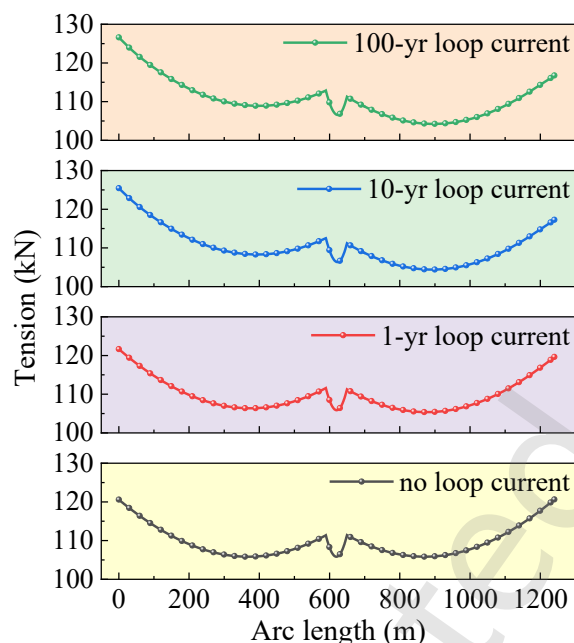


Fig.14 (a) Configuration; (b) Curvature; (c) Axial tension force.

Parameter analysis shows that increasing the buoy length can significantly reduce the tension on the cable, but it also significantly increases the curvature of the cable. When keeping the total buoy length constant and only adjusting the buoy positions, for the same number of buoy groups, increasing the buoy spacing does not lead to a pure increase or decrease in tension and curvature; instead, extreme values occur in a certain range. For different numbers of buoy groups, when increasing from 1 group to 2 groups, both tension and curvature decrease significantly. However, further increasing to 4 groups or 8 groups results in negligible changes.

## 5. Conclusions

This paper proposes a rapid and straightforward method for the static analysis of fully suspended inter-array cables in offshore wind farms. The main research work is as follows:

1. Based on the principle of minimum total potential energy, the static governing equations of fully suspended inter-array cables in offshore wind farms are derived. The finite difference method is used for equation discretization, and the Newton-Raphson iterative algorithm is introduced to numerically solve the nonlinear equations.

2. Comparative simulation verification is performed using self-compiled MATLAB programs and the commercial software OrcaFlex. Results indicate that the

calculated results of the proposed method are highly consistent with the OrcaFlex simulations in terms of cable configuration, bending curvature, bending force, and axial tension, with a maximum error of less than 1%.

3. The advantages and disadvantages of fully suspended and free-suspension cable configurations in offshore engineering applications are briefly discussed from three aspects, including static mechanical analysis in preliminary cable design, power transmission, and on-site installation.

4. The influences of buoy length, buoy arrangement, and ocean current conditions on the structural configuration, effective tension, and bending curvature of fully suspended cables are further analyzed. The research results provide an important theoretical basis and reference for the configuration optimization and engineering design of offshore wind farm cables.

### **Acknowledgements**

None.

### **Author contribution statement**

Maolong Wang is responsible for conceptualization, methodology development, numerical modeling, result validation, parametric analysis, and original manuscript drafting. Depeng Liu participates in manuscript review and editing. Zhiqiang Hu contributes to manuscript review and editing. Yu Zhang undertakes manuscript review and editing, research supervision, and project administration. All the authors have approved the final manuscript.

### **Data availability**

The data that support the findings of this study are included in the article is available from the corresponding author upon reasonable request.

### **Declaration of competing interest**

All the contributing authors report no conflicts of interest in this work.

### **Funding**

This research was financially supported by the National Key R&D Program of China (Grant No. 2024YFC2814801)

### **Use of AI statement**

None.

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Just Accepted