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Qualitative and Quantitative Analysis of the Stability of Conductors in Riserless Mud Recovery System

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Abstract: Riserless Mud Recovery (RMR) technology, as an emerging and efficient drilling method, is advantageous to reduce the shallow flow hazards and the number of casings. The wave current effect is one of the reasons limiting the application of RMR technology in deep and ultra-deep water, and fewer quantitative and qualitative analyses of the effect of the current are made on the stability of conductors. This paper investigates the influence of the overturning moment generated by the continuous subsea internal wave flow and the soil resistance to the conductor. The numerical simulation software ABAQUS is used to study the effects of sea state recurrence period, seabed soil properties, conductor material, driving depth in the mud, and conductor wellhead height on the stability of the conductor, and the influence weights of the factors affecting the stability of the conductor are analyzed using the weight analysis algorithm of extreme learning machine-mean impact value (ELM-MIV). Finally, the qualitative and quantitative analyses affecting the stability of the conductor are carried out, which provide reference values for the application of the RMR technology.

Keywords: RMR technology; influencing weights; quantitative analysis; conductor stability



Citation: Qin, R.; Xu, B.; Chen, H.; Lu, Q.; Li, C.; Wang, J.; Feng, Q.; Liu, X.; Wang, L. Qualitative and Quantitative Analysis of the Stability of Conductors in Riserless Mud Recovery System. *Energies* **2022**, *15*, 7657. <https://doi.org/10.3390/en15207657>

Academic Editor: Hossein Hamidi

Received: 10 August 2022

Accepted: 13 October 2022

Published: 17 October 2022

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1. Introduction

Offshore oil and gas resources are abundant, but deep-water drilling is confronted with more technical challenges such as harsh environments, formation fracture, narrow pore pressure windows, and the need for placing more casings to maintain borehole stability [1–4]. Dual gradient drilling is an unconventional drilling technique that controls the annular pressure of the borehole by varying the pressure gradients in the annulus of a bulkhead by using a pump or changing the fluid density [5–9]. RMR [10–12] can implement dual gradient drilling, which forms a closed mud circulation system with recoverable mud. RMR technology is advantageous to reduce shallow flow hazards, protect the marine environment, reduce the number of casings, and optimize the borehole structure [13–16].

The first patent was filed in 1969 for the first well-drilling technology without risers [17,18]. Subsequently, AGR developed the RMR technology based on the rock chip transfer system (CTS) developed by itself [19]. The first commercial application was in 2003 in the West Azeri field in the Caspian Sea, with 15 wells completed [20,21]. The RMR was introduced to an offshore drilling project in a remote area of Sakhalin Island in the Russian Far East, where the operating conditions were harsh, ultimately resulting in an increase in operational efficiency and the zero discharge of rock chips [22,23]. RMR was first applied in the eastern Atlantic North Sea, completed drilling of a 113 m water depth, saved the drilling time, reduced marine pollution, and reduced operating costs [24–26]. A joint industrial project DEMO 2000 consisting of AGR Subsea, BP America, Shell, and the Norwegian Research Council was launched to advance deep-water RMR, and completed drilling of a 1419 m water depth at the offshore site in Sabah, Malaysia in September [27,28]. BP used RMR

technology in the sea of Egypt to eliminate the effect of formation fractures and improve efficiency by eliminating the use of drill tailpipe [29]. RMR was applied to the sea off Australia, successfully solved the problem of loose sandstone in Browse Basin, deepened the surface casing, and completed more than 40 wells with a water depth of 450 m [30–32]. RMR was first applied in the Gulf of Mexico, saving three times the drilling fluid and increasing the operational efficiency, and improving the overall borehole structure [33,34]. RMR technology was applied in Sabah, Malaysia, and achieved perfect cementing of top-hole surface casing in the Malikai deep-water oil field [35]. RMR was specially applied to the Zumba Well in Norway to avoid the discharge of drilling fluids and rock chips into the seafloor, protecting a large number of corals in the vicinity of the well [36–38]. RMR was also coupled with the casing drilling for geohazard risk mitigation [39,40]. Currently, RMR has been widely used in shallow water, deep water, and the Integrated Ocean Drilling Program (IODP) is working together with AGR and other companies to study RMR technology for ultra-deep water (>3657 m) [41]. Li et al. [42] studied the effect of different pump volumes and drilling fluids on the variation of drill pipe temperature. Froyen et al. [43] simulated the scenario of shallow gas during the drilling by an RMR system and obtained that RMR could effectively reduce the gas influx. Kotow et al. [44] optimized the RMR technique for casing in deep-water wells in the Gulf of Mexico and reduced the drilling time and cost. Li et al. [45] analyzed the factors affecting the efficiency of recovering rock chips within the RMR system pipeline. Wang et al. [46] analyzed the effect of rig motion on drill pipe vibration and wellhead pressure. Liu et al. [47] analyzed the forces on the drill pipe and casing in the RMR system and developed an overall static model of the wellhead and a dynamic model of the drill pipe. Mao et al. [48] analyzed the effect of high-pressure gas on RMR drilling pressure and modeled the correlation. Wang et al. [49] analyzed the composite casing drilling technology in the RMR construction and proposed the optimization measures based on a particular site. Obadina et al. [50] analyzed the effects of water flow and drillships on the forces on the drill pipe during the RMR construction and performed the corresponding model simulation analysis.

Therefore, the current research on RMR technology is mainly focused on the application research and stress analysis of drill pipe. Subsea currents can produce a shear force on the structures during drilling, damaging the tubular columns and other structures and threatening operational safety. Therefore, the wave current effect is one of the reasons limiting the application of RMR technology in deep and ultra-deep water, and fewer quantitative and qualitative analyses of the effect of the current are made on the stability of conductors. This paper investigates the influence of the overturning moment generated by the continuous subsea internal wave flow and the soil resistance to the conductor. The numerical simulation software ABAQUS is used to study the effects of sea state recurrence period, seabed soil properties, conductor material, driving depth in the mud, and conductor wellhead height on the stability of the conductor. The stability of the conductor under the ultimate working conditions was verified. With the ELM-MIV weight analysis algorithm, the influence weights and the correlation of the factors influencing the stability of the catheter are quantified and analyzed.

2. RMR Technology

Unlike land-based exploration and development, offshore drilling projects are confronted with extremely complex environmental conditions. Therefore, RMR technology is generally popular in the exploitation of deep-sea oil and gas resources at present. RMR technology eliminates the use of drilling traps, and mud rock chips are circulated through a separate mud return line, where the drill pipe and mud return line are directly exposed to the seawater.

Generally, the RMR drilling system mainly consists of a drilling unit, a mud return system unit, a mud treatment unit, and a power monitoring unit. A schematic diagram of the structure of RMR system is shown in Figure 1. The drilling unit consists of an exploration vessel, a drill pipe, a derrick, a downhole drilling tool, a casing, conductor and

a subsea suction module for rock breaking and drilling to extract the core. The upper of the drill pipe is connected to the exploration vessel and the lower of the borehole runs through the suction module, which isolates the external seawater from the borehole annulus through the sealing assembly of the suction module. The mud return system includes a subsea anchor device, a subsea pump set, a mud return pipeline, a pipeline docking joint, and a lowering installation platform for lifting rock chip mud from the seabed to the exploration vessel to realize the recycling of mud. The mud treatment unit includes a mud purification unit, a drilling fluid cooling unit, a vibrating screen, and a mud manifold, which purifies, inhibits, and cools the rock chip mud, and transports it through the mud manifold to the drill pipe for re-entry into the subsea for drilling. The power and monitoring system consists of electrical equipment containers, console containers, and power control lines to power, monitor, and control the slurry lifting system.

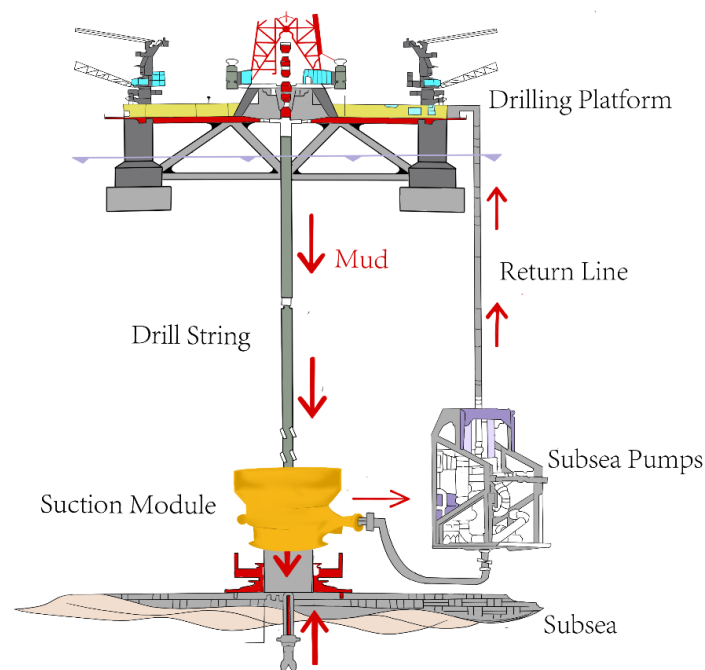


Figure 1. Schematic diagram of the structure of the RMR system.

The advantages of RMR technology include: (1) eliminating the use of drilling septic pipes, blowout preventers, and related equipment, lowering the requirements on the vessel's load-bearing capacity and reducing the drilling cost; (2) deepening the surface casing to cross the shallow danger zone, reducing the danger from the shallow gas; (3) reducing the use of drilling mud, cementing cement and casing, reducing the variable load on the vessel; (4) the closed-circulation pathway of septic-free mud drilling system has been formed before the use of mud, so no mud will flow into the ocean during operation, protecting the marine ecological environment. The disadvantages mainly include: (1) most of the current international commercial applications are for shallow drilling; (2) the emergency evacuation system is not perfect, well control during cementing and casing cannot be guaranteed, and a detailed safety assessment is required.

3. Theory and Models

3.1. Conductor Analysis Model

The RMR drilling system adopts the Riserless technology to eliminate the use of conventional drilling risers. With the drill column directly into the seawater and the subsea suction module mounted on the wellhead, it can isolate the seawater from the returning drilling mud and seal the borehole from the seawater. In the RMR drilling system, the drilling fluid is pumped into the drill pipe by the surface pump and reaches the bottom of the

the well through the drill pipe, which will shock and break the rock, and carry the rock chips back up from the borehole annulus, where it will be diverted into the subsea lift pump set by the subsea suction device at the top of the annulus. The rock chips and the drilling fluid will flow back to the drilling platform through the mud return pipeline under the action of the subsea pump. The suction module and the conductor can be considered to be rigidly connected. Therefore, the conductor is mainly subjected to the soil resistance forces and the current forces transmitted by the suction module when performing subsea operations.

Depending on the structure and function of the suction module, the drill pipe passes through and performs rotary drilling operations inside it, but the drill pipe does not interact with itself. Meanwhile, deep-water drilling rigs with dynamic positioning can remain relatively stationary at the surface with a range of accuracy relative to the wellhead intake module. The drilling pipe is connected to the drilling platform at the upper end and drilled into the subsea strata at the lower end, which can be approximated structurally as a simply supported beam restrained at both ends with minimum deflection at the restraint. Therefore, the flexural deformation of the drill pipe at the subsea mud surface is minimized so that it does not interfere with the suction module. Lastly, the suction module is connected to the subsea slurry lift pump set by a flexible crossover tube. In the design, the crossover tube uses a flexible rubber material tube as the base tube, with buoyancy blocks and other materials to make a zero-gravity tube. In addition, in the designed working conditions, the crossover pipe is part of the slurry return pipe and is a low-pressure working pipe, so its own tensile strength and the design of the connections are designed for low strength and cannot withstand higher tensile forces. At the application level, the span hose is usually used which is larger than the spacing between the suction module and the subsea lift pump group to connect the two units, which can ensure the normal operation of the subsea suction module without disturbing the subsea pump group even if the subsea pump group sinks and rises with the rig in the severe sea condition. The overall force state diagram of the RMR system is shown in Figure 2.

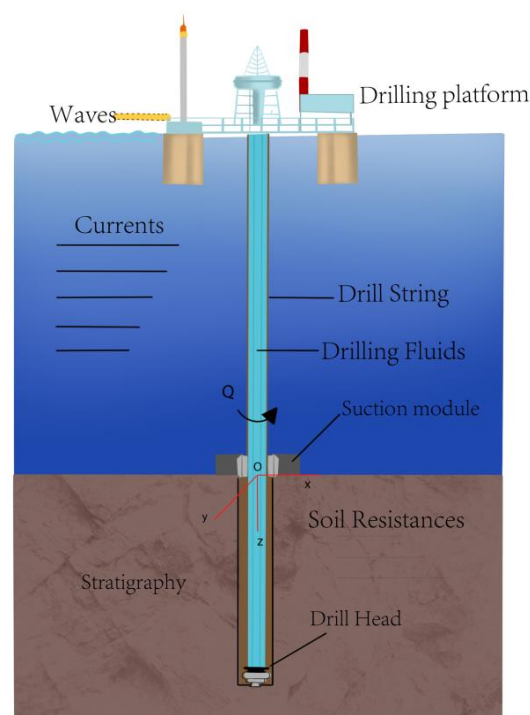


Figure 2. Overall force state diagram.

3.2. Simulation Methods for Conductor-Soil Interactions

The composite foundation reaction method is commonly used for analyzing the interaction between structures and soils. Winkler foundation model adopted in the composite foundation reaction method to discrete the soil around the structure as a spring acting individually, and when one of the springs is stressed, it will undergo the compression proportional to the force applied, without affecting other springs. The composite foundation reaction method is widely used in the P-y curve method, which can simulate the elasticity of submarine soil well and analyze the lateral bearing capacity of the structure with large displacement more accurately. The P-y curve method refers to the relationship curve between the soil reaction force P at the depth x under the soil and the lateral deformation y. It integrates the characteristics of the non-linearity of the soil around the pile, the stiffness of the pile, and the nature of the external loading effect, and is a kind of elastic-plastic analysis method [51,52].

(1) P-y curves in soft clay soils

For soft clay soils with undrained shear strength $C_u \leq 96 \text{ kPa}$ the ultimate soil resistance per unit pile length at seabed x depth is determined by Equation (1).

$$\begin{cases} P_u = 3C_u + \gamma_c x + \frac{\xi C_u x}{D}, x < x_r \\ P_u = 9C_u, x \geq x_r \\ x_r = \frac{6C_u D}{\gamma_c D + \xi C_u} \end{cases} \quad (1)$$

The P-y curve of soft clay soil under static load can be determined by Equation (2).

$$\begin{cases} y_{50} = 2.5\varepsilon_{50}D \\ \frac{P}{P_u} = 0.5\left(\frac{y}{y_{50}}\right)^{\frac{1}{3}}, \frac{y}{y_{50}} < 8 \\ P = P_u, \frac{y}{y_{50}} > 8 \end{cases} \quad (2)$$

(2) P-y curves in hard clay

For the hard clay soil with undrained shear strength $C_u > 96 \text{ kPa}$ Equation (1) is adopted for individual calculation, and the smaller value is taken as the ultimate soil resistance on the unit structural member. The P-y curve of the hard clay soil under static load can be determined by Equation (3).

$$\begin{cases} \frac{P}{P_u} = 0.5\left(\frac{y}{y_{50}}\right)^{\frac{1}{4}} & 0 < \frac{y}{y_{50}} < 16 \\ \frac{P}{P_u} = P_u & \frac{y}{y_{50}} \geq 16 \\ y_{50} = b\varepsilon_{50} \end{cases} \quad (3)$$

Typical soil loads on the conductor are shown in Figure 3. The interaction between soil and conductor is modeled by ABAQUS, a large general-purpose finite element analysis software, to discretize the shallow submarine soil and calculate the P-y relationship of the soil at each discretized layer. A nonlinear spring element is added at the corresponding node of the structural finite element model of the conductor to simulate the soil resistance of the conductor at that point, and the spring stiffness is given by the P-y curve. The deformation of the conductor is solved by the following equilibrium equation.

$$EI \frac{d^4 y}{dz^4} = p \quad (4)$$

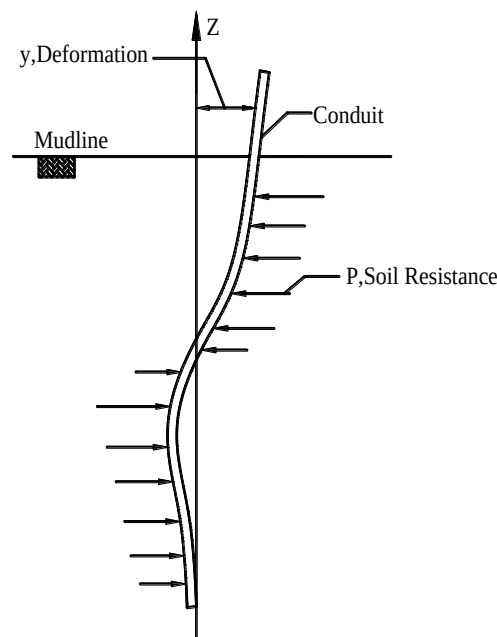


Figure 3. Soil load acting on the conductor.

3.3. Simulation Method of Current Load Effect

(1) Drag load

When the constant uniform water flows around the circular structural members, the force on the circular structural members along the flow direction is called the drag force. The drag force is generally composed of two parts: friction drag force and differential pressure drag force. The drag force on a unit length of a structural member can be determined by Equation (5).

$$f_c = \frac{1}{2} \rho D_C C_D v |v| \quad (5)$$

(2) Inertia load

As to the load of the bypassing fluid on the circular structural member in the non-constant bypassing motion, in addition to the drag force, there is an inertial force from the accelerated fluid. The winding inertia force on the structural member from the accelerated fluid along the flow direction can be determined by Equation (6).

$$f_I = \rho C_M \frac{\pi D_C^2}{4} \frac{du}{dt} \quad (6)$$

The lateral load on the wellhead unit on the seabed is mainly the current force. For the pure current case, the current force per unit length is shown in Equation (7) [53].

$$f = \frac{1}{2} \rho D_C C_D v |v| + \rho C_M \frac{\pi D_C^2}{4} \frac{du}{dt} \quad (7)$$

3.4. ELM-MIV Weighting Analysis Algorithm

Extreme learning machine (ELM) is a new single hidden layer and feedforward neural network algorithm. Mean impact value (MIV) can be used to evaluate the influence weight of the influencing factors of the input layer on the breakdown probability of the output layer [54,55]. The ELM-MIV weight analysis method [56] is a hybrid algorithm based on the extreme learning machine and mean impact value, which is trained by the extreme learning machine data and then predicts the maximum displacement of the conductors with different parameters. The mean impact value algorithm is used to calculate the correlation among the influencing factors and the maximum displacement of the conductors and to

determine the weight value of each influencing factor. According to the ELM network structure, the following formula can be obtained.

$$H\beta = T \quad (8)$$

The data are trained in such a way that the error between $H\beta$ and Y is minimized.

$$\|H(\hat{w}_i, \hat{b}_i)\hat{\beta} - Y\| = \min_{\beta} \|H\beta - Y\| \quad (9)$$

The mean impact value of the influencing factor i can be calculated by the following equation.

$$MIV_i = \frac{1}{m} \sum_{j=1}^m (t_{ij}^+ - t_{ij}^-) \quad (10)$$

The impact weight value of each influencing factor on the output value can be expressed as Equation (11).

$$C_i = \frac{|MIV_i|}{\sum_{i=1}^n |MIV_i|} \quad (11)$$

4. Analysis of Factors Influencing the Stability of the Conductor

ABAQUS finite element analysis software is adopted to establish the conductor model using a two-dimensional linear model, adding conductor material and cross-section, adding displacement fixed constraints due to the small displacement at the bottom of the conductor, and adding currents loads using the ABAQUS/Aqua module. The effects of sea state recurrence period, seabed soil properties, conductor material, conductor mud entry depth, and conductor wellhead height on the stability of the conductor are studied, which can provide reference guidance for actual operation. The basic information about a well drilled in a deep-water area is shown in Tables 1 and 2.

Table 1. Environmental parameters of the regional well.

	Depth	Recurrence Period			
		1 Year	5 Years	10 Years	25 Years
Current (m/s)	10 m	0.68	1.40	1.49	1.59
	20 m	0.66	1.39	1.48	1.57
	30 m	0.70	1.36	1.46	1.57
	50 m	0.45	1.35	1.46	1.58
	75 m	0.57	1.29	1.40	1.53
	100 m	0.48	1.21	1.31	1.42
	150 m	0.44	0.99	1.06	1.14
	200 m	0.43	0.81	0.86	0.91
	250 m	0.40	0.75	0.81	0.87
	300 m	0.35	0.73	0.77	0.82
	500 m	0.35	0.56	0.61	0.67
	1000 m	0.30	0.41	0.45	0.49

Table 2. Basic parameters.

Basic Parameters	Value	Basic Parameters	Value
Seabed depth (m)	1000	Poisson's ratio of 45# steel	0.26
Conductor length (m)	94	Poisson's ratio of copper-nickel alloy tube	0.34
Outside diameter of conductor (mm)	914.4	Density of Q235	7930
Conductor wall thickness (mm)	38.1	Density of stainless steel tube	7850
Seawater density (kg/m ³)	1034	Density of 45# steel	7850
Modulus of elasticity of Q235 (GPa)	210	Density of copper-nickel alloy tube	8908
Modulus of elasticity of stainless steel tube (GPa)	190	Soil K1 average	1.78×10^6
Modulus of elasticity of 45# steel (GPa)	200	Soil K2 average	3.02×10^7
Modulus of elasticity of copper-nickel alloy tubes (GPa)	150	Soil K3 average	1.54×10^8
Poisson's ratio of Q235	0.3	Soil K4 average	5.75×10^6
Poisson's ratio of stainless steel tube	0.3	Drag force coefficient	0.7

4.1. Qualitative Analysis of Conductor Stability

4.1.1. Analysis of the Effect of Sea State Recurrence Period on Conductor Stability

The analysis results of the effect of different sea state recurrence periods on the stability of the conductor in the selected well of 1000 m water depth are shown in Figure 4. The results show that all stability parameters in the upper of the conductor increase significantly with the increase in flow rate. The effect of sea state recurrence period on conductor displacement and turning angle is mainly concentrated within 25 m depth, and the effect decreases above 25 m, and the effect on conductor bending moment and equivalent stress is obvious within 35 m depth. When the sea state recurrence period increases, the growth rate of conductor upper displacement and turning angle accelerates, and the changes in the rate of peak of conductor bending moment and equivalent stress also accelerate.

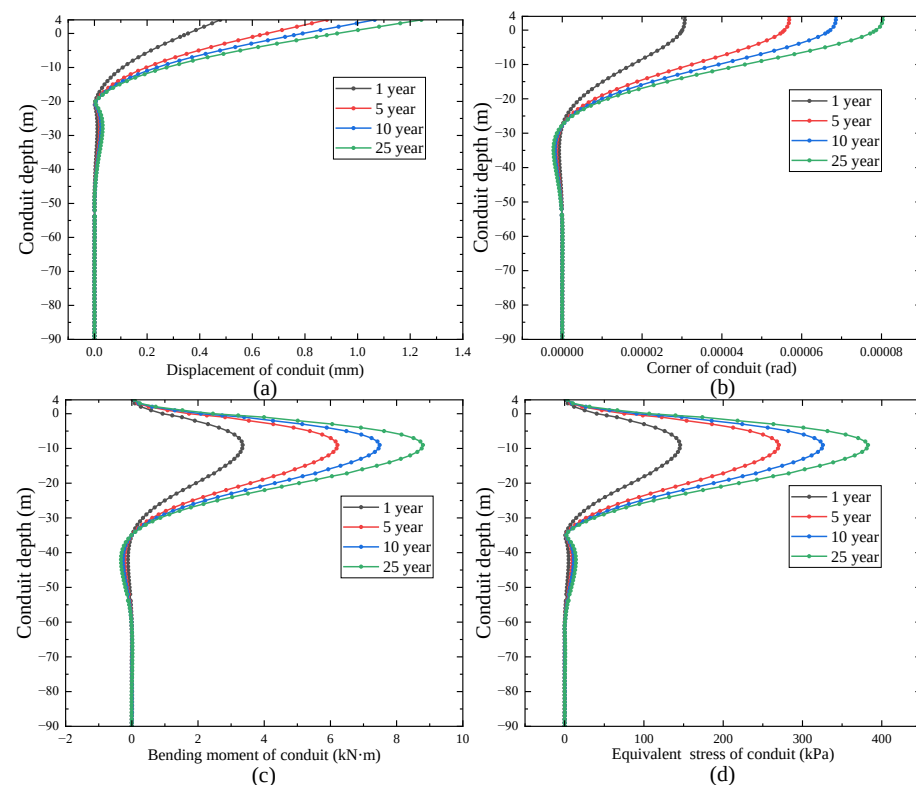


Figure 4. (a) Effect of sea state return period on conductor displacement, (b) Effect of sea state return period on conductor rotation angle, (c) Effect of sea state return period on conductor bending moment, (d) Effect of sea state return period on conductor equivalent force.

The value of displacement and the angle of rotation of the conductor in different sea state recurrence periods reach a peak at the uppermost part where it is subjected to the action of currents, while the bending moment and equivalent stress due to the soil reaction force occur at a depth of 10 m or so. Therefore, the impact from a strong typhoon should be monitored, and the deflection of the conductor increases before the arrival of a strong typhoon, and measures should be taken to ensure the stability of the conductor if necessary.

4.1.2. Analysis of the Effect of Seabed Soil Properties on Conductor Stability

When the upper of the conductor receives a load, the conductor in the soil will receive the soil resistance, the bearing capacity of different soils differs from each other, so it will have an effect on the conductor stability. The higher the stiffness factor of the soil, the harder the soil, and the results are shown in Figure 5. The results show that all stability parameters of the part of the conductor within 30 m depth decrease with the increase in the stiffness coefficient of the soil. The displacement and turning angle of the part of the conductor above 30 m depth do not change with the soil, which can be deemed that the soil imposes fixed constraints on the lower conductor. Due to the different soil depth distributions, it can be seen that different soil conditions have different turning points for each of their stability parameters affecting the conductor, but the turning influence trends are roughly the same.

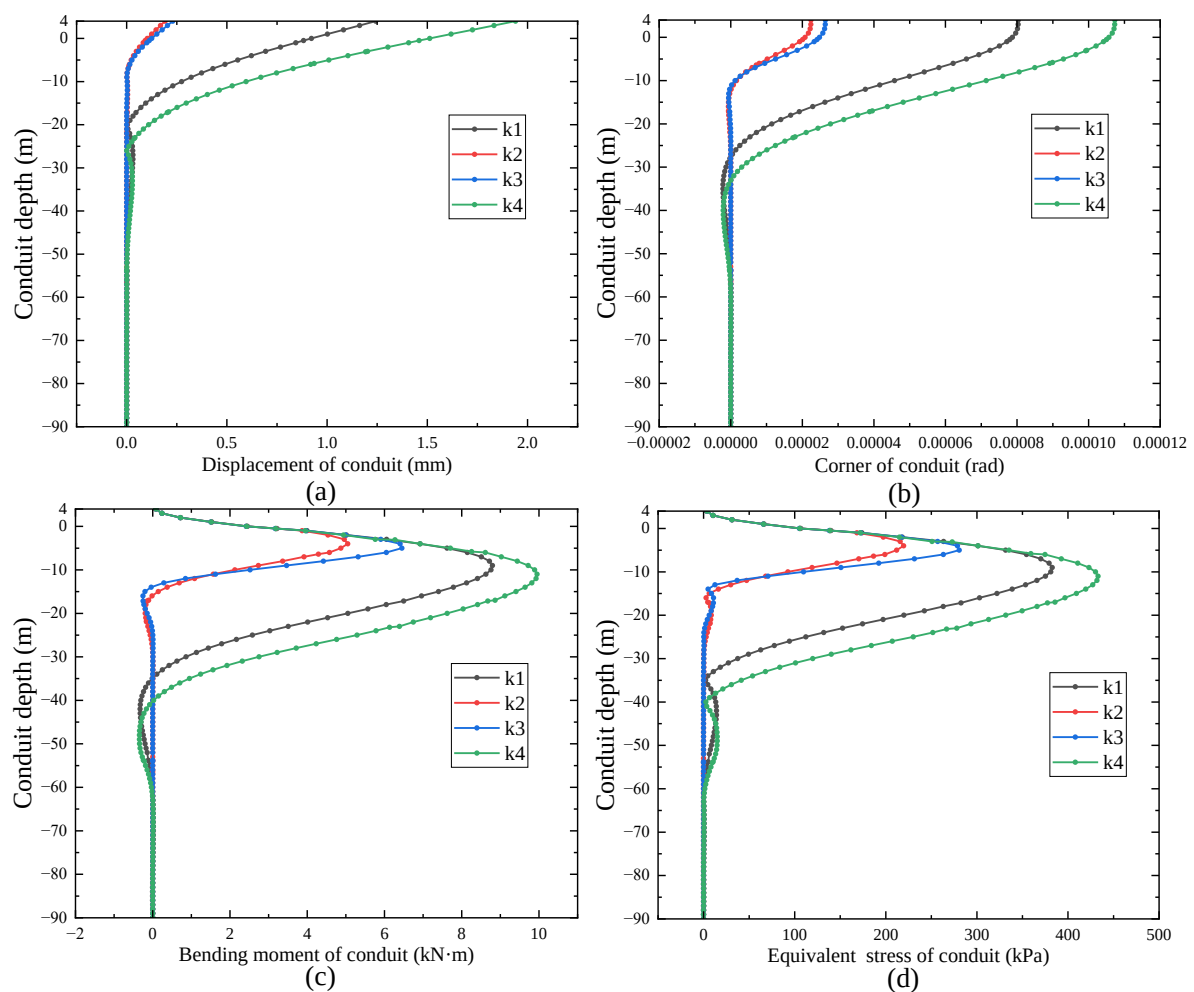


Figure 5. (a) Effect of seabed soil properties on conductor displacement, (b) Effect of seabed soil properties on conductor turning angle, (c) Effect of seabed soil properties on conductor bending moment, (d) Effect of seabed soil properties on conductor equivalent force.

4.1.3. Analysis of the Influence of Conductor Material on Conductor Stability

The results of the effect of common conductor materials on conductor stability are shown in Figure 6. The results show that the displacement and turning angle of the conductor increase with the decrease in the elastic modulus of the conductor material; the opposite is true for the bending moment and equivalent stress of the conductor. The effect of conductor material on the displacement and turning angle is mainly concentrated within 20 m depth. The effect on bending moment and equivalent stress is mainly concentrated within 30 m depth. Since the elastic modulus of the conductor material is very close to the rigid body, the current common conductor material has few effects on the various stability parameters of the conductor, and other factors such as corrosion resistance should be considered in selecting the conductor materials.

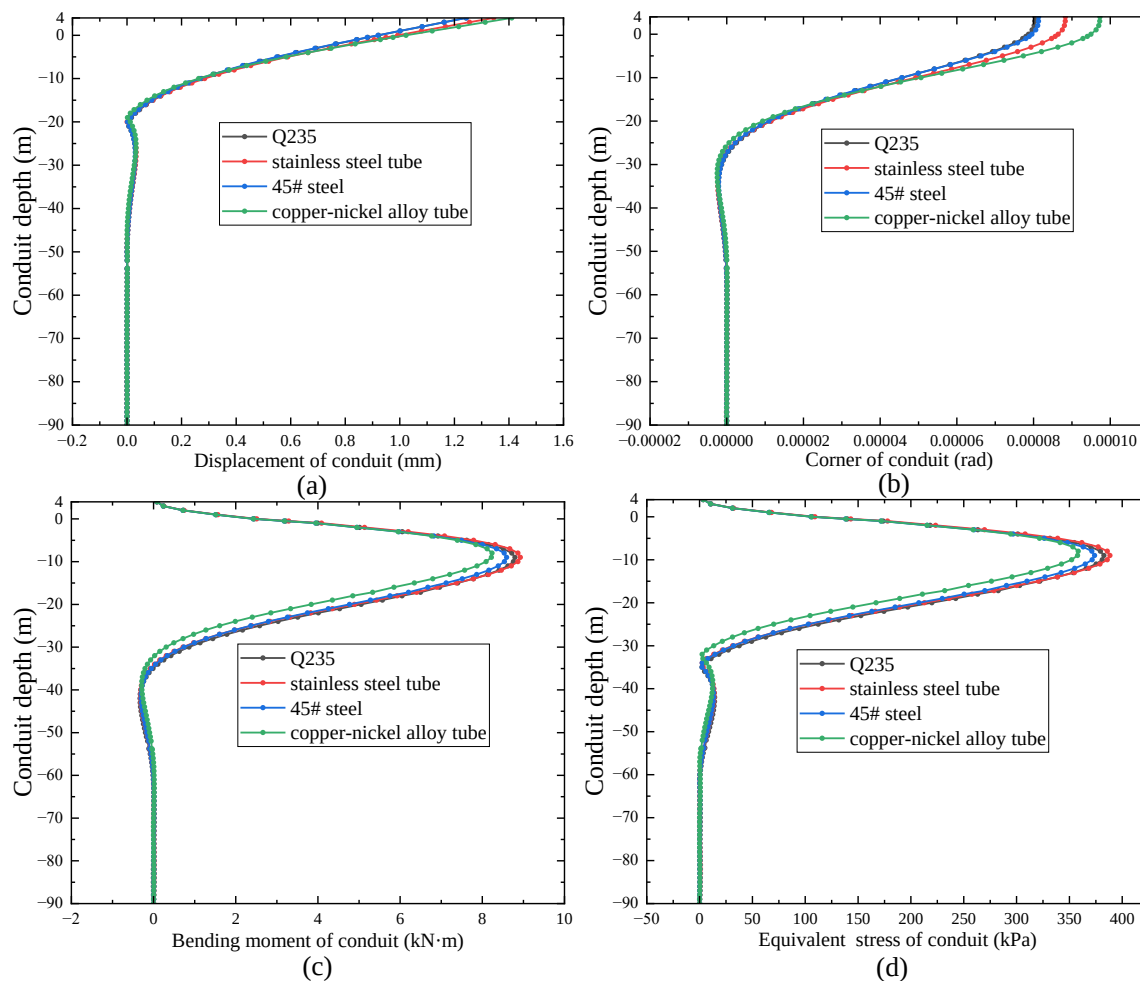


Figure 6. (a) Effect of conductor material on conductor displacement, (b) Effect of conductor material on conductor turning angle, (c) Effect of conductor material on conductor bending moment, (d) Effect of conductor material on conductor equivalent force.

4.1.4. Analysis of the Effect of Driving Depth in the Mud on Conductor Stability

Set the driving depth of conductor in the mud as 90, 80, 70, 60, 50, 40, 30, 20, and 10 m, and the results of its effect on the conductor stability are shown in Figure 7. The results show that the displacement and turning angle of the conductor increase with the decrease in the driving depth, and the increase in the displacement and turning angle of the conductor is small when the driving depth is 30–90 m. When the driving depth decreases to 20 m, the displacement and turning angle of the conductor start to increase significantly; when it decreases to 10 m, the displacement and turning angle of the conductor happen

to increase sharply. It can be inferred that the minimum driving depth of the conductor in the mud is about 20 m in this soil condition. For both conductor bending moment and equivalent stress, the turning point is about 5 to 10 m. Within the driving depth of 30 m, both conductor bending moment and equivalent stress change obviously, and when the driving depth exceeds 30 m, both conductor bending moment and equivalent stress gradually decreases to 0. Therefore, the effect of the conductor depth in the mud on the stability of the conductor is more obvious, when the driving depth is too small, it will lead to excessive conductor deflection in the limited working conditions and it should be designed according to the reasonable soil entry depth.

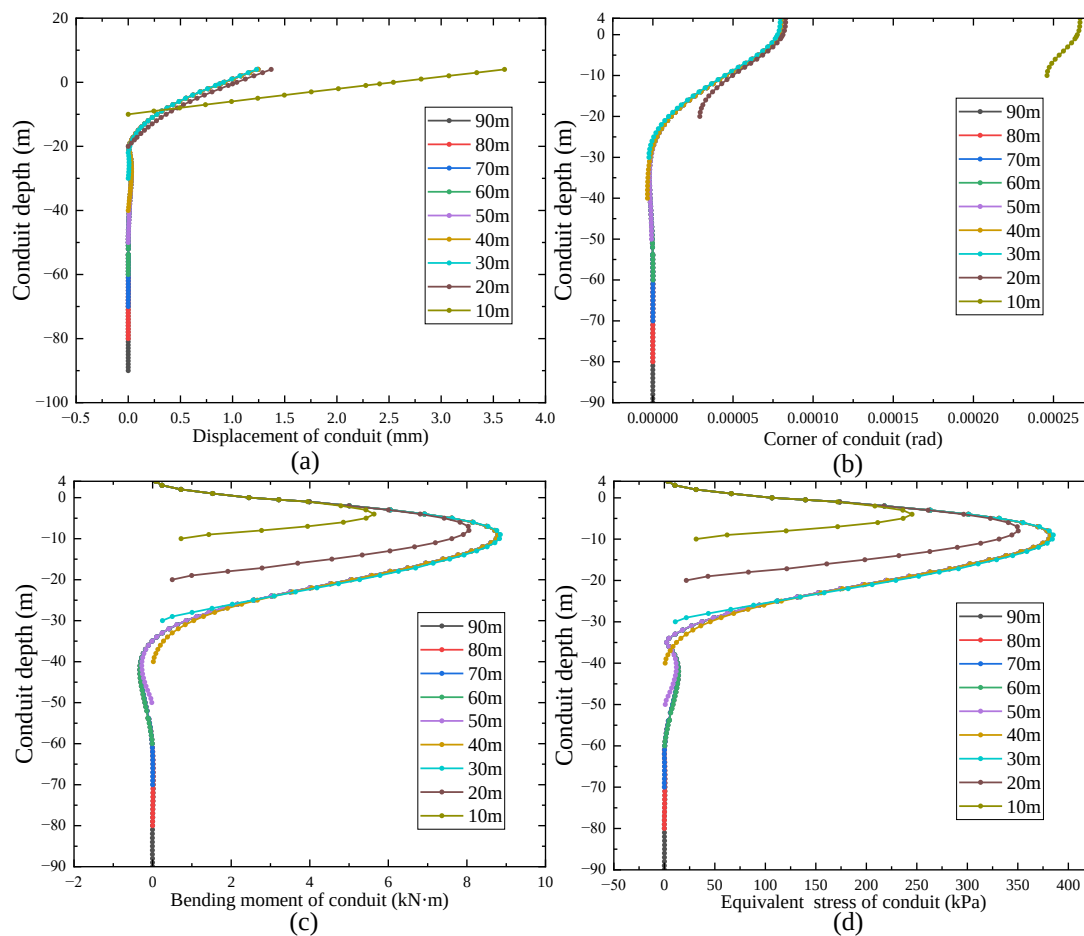


Figure 7. (a) Effect of driving depth on conductor displacement, (b) Effect of driving depth on conductor turning angle, (c) Effect of driving depth on conductor bending moment, (d) Effect of driving depth on conductor equivalent force.

4.1.5. Analysis of the Effect of Conductor Wellhead Height on the Stability of the Conductor

The conductor wellhead height determines the length of the environmental load to which the conductor is subjected, and this paper selects 1, 2, 3, 4, 5, 6, 7, 8, and 9 m as the conductor wellhead height, respectively. The results of their effects on the conductor stability are shown in Figure 8. The results show that the conductor displacement, turning angle, bending moment, and equivalent stress all increase with the height of the conductor wellhead just because the conductors on the seabed are subjected to seawater flow. The effect of conductor wellhead height on the conductor mainly acts at a depth within 20 m. When it exceeds 20 m, the changes in each stability parameter are small. Meanwhile, the conductor wellhead height increases, and the turning and peak points of the bending moment and equivalent stress remain the same, both at a depth of 40 m and 10 m or

so. The conductor wellhead height has a great effect on the stability of the conductor, so appropriately reducing the height of the conductor wellhead can effectively improve the stability of the conductor.

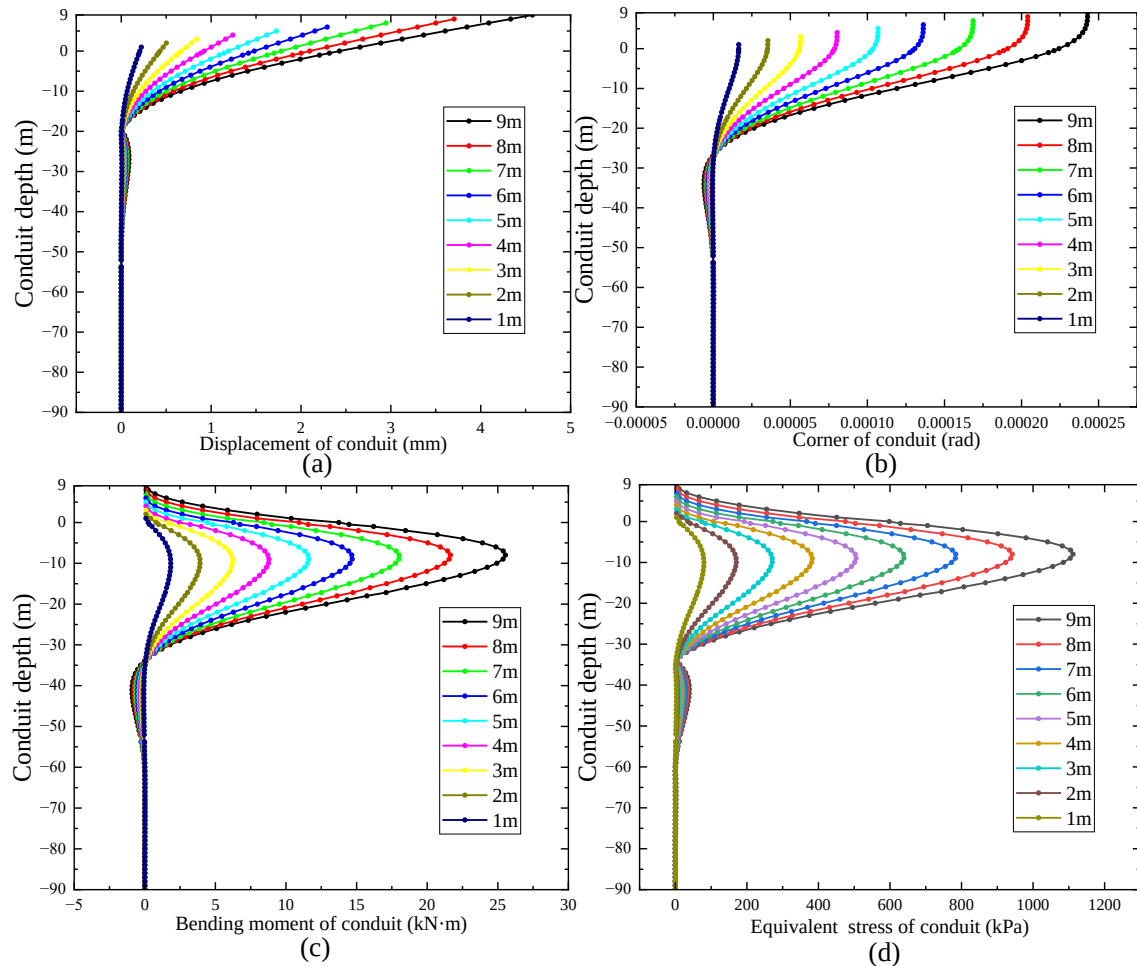


Figure 8. (a) Effect of conductor wellhead height on conductor displacement, (b) Effect of conductor wellhead height on conductor turning angle, (c) Effect of conductor wellhead height on conductor bending moment, (d) Effect of conductor wellhead height on conductor equivalent force.

4.1.6. Conductor Stability Analysis under Extreme Operating Conditions

Based on the analysis of the individual factors mentioned above, the most dangerous case of each factor is selected to form this extreme working condition. The extreme working conditions are selected as flow velocity 1.49 m/s, mud entry depth 10 m, conductor material copper-nickel alloy pipe, soil k4, and wellhead height 9 m.

The results of various parameters of the conductor stability are shown in Table 3. The ultimate displacement and turning angle of the conductor reach 0.54 m and 0.027 rad, and it is still safe to meet the deflection angle of 1° at a conductor depth of 90 m in the mud [57]. The ultimate bending moment and equivalent stress of the conductor are also much smaller than the failure strength of the conductor, ensuring the safety of the operation. However, the ultimate working conditions still should be avoided, and the most suitable operating conditions should be selected under the condition of both cost and safety.

Table 3. Conductor stability parameters under extreme operating conditions.

Ultimate Displacement (m)	Ultimate Corner (rad)	Ultimate Bending Moment (kN·m)	Ultimate Equivalent Stress (MPa)
0.5369	2.699×10^{-2}	210.2	14.23

4.2. Quantitative Analysis of Factors Influencing the Stability of Conductor

Conductor stability is affected by multiple factors, and weight analysis is required to determine the influence weight of each influencing factor. The effect of each influencing factor on the relevance of the conductor stability is verified using a weight analysis based on the extreme learning machine-average impact value, and the influence weights of each influencing factor were determined.

According to the analysis of conductor stability, the main factors affecting the stability of the conductor include sea state recurrence period, mud line depth, soil properties, conductor material, mud entry depth, and conductor wellhead height. Based on the available data, the level of each factor is set as shown in Table 4, and ABAQUS is used to simulate and calculate the maximum displacement of the conductors with different influencing factors. For machine learning, soil properties and conductor material data are required. k_1 , k_2 , k_3 , and k_4 are taken as the equivalent spring stiffness coefficients of the soil resistance, respectively. The modulus of elasticity is taken for Q235, 45-gauge steel, stainless steel tubes, and copper-nickel alloy tubes, respectively. According to the orthogonal level number, a hybrid orthogonal experiment is designed, and the simulation yielded the maximum displacement of the conductors with different influencing factors, and the input data of the weight analysis based on ELM-MIV are shown in the Appendix A.

Table 4. The setting of each factor level of conductor stability.

Sea State Recurrence Period	Seabed Depth	Soil Properties	Conductor Material	Mud Entry Depth	Height of Conductor Wellhead
1 year	10 m	K1 (1784066)	Q235 (2.11×10^{11})	10 m	1 m
5 year	20 m	K2 (30156639)	45# steel (2×10^{11})	20 m	2 m
10 year	30 m	K3 (154022319)	stainless steel tube (1.9×10^{11})	30 m	3 m
25 year	50 m	K4 (5752930)	copper-nickel alloy tube (1.5×10^{11})	40 m	4 m
/	75 m	/	/	50 m	5 m
/	100 m	/	/	60 m	6 m
/	150 m	/	/	70 m	7 m
/	200 m	/	/	80 m	8 m
/	250 m	/	/	90 m	9 m
/	300 m	/	/	/	/
/	500 m	/	/	/	/
/	1000 m	/	/	/	/

When the limit learning machine is used for training and learning, the first 61 group data are adopted as training samples and the last 20 sets of data are adopted as test samples, and then the prediction model based on the limit learning machine is trained and evaluated, and the prediction results of the test samples are shown in Table 5. From the table, it can be concluded that the MSE values of the evaluation indexes tested by the model are small and the prediction error is small, which proves the feasibility of the extreme learning machine for data training. The weight of each influencing factor is evaluated according to the MIV-algorithm-based training model, where the positive and negative MIV values represent the positive and negative correlation of the influencing output values, and the MIV values and weight values of each influencing factor are shown in Table 6.

Table 5. Prediction results of the test samples.

SN	Actual Value	Predictive Value	Serial Number	Actual Value	Predictive Value
1	1.87×10^{-2}	1.85×10^{-2}	11	8.64×10^{-3}	8.60×10^{-3}
2	4.10×10^{-4}	4.60×10^{-4}	12	4.48×10^{-2}	4.28×10^{-2}
3	1.51×10^{-2}	1.53×10^{-2}	13	1.19×10^{-2}	1.29×10^{-2}
4	4.64×10^{-4}	4.68×10^{-4}	14	4.66×10^{-4}	4.64×10^{-4}
5	5.95×10^{-4}	5.91×10^{-4}	15	5.86×10^{-4}	5.84×10^{-4}
6	3.11×10^{-3}	3.17×10^{-3}	16	2.26×10^{-4}	2.25×10^{-4}
7	2.26×10^{-2}	2.22×10^{-2}	17	1.06×10^{-3}	1.36×10^{-3}
8	4.09×10^{-2}	4.18×10^{-2}	18	1.27×10^{-3}	1.24×10^{-3}
9	1.39×10^{-3}	1.35×10^{-3}	19	1.26×10^{-3}	1.29×10^{-3}
10	4.70×10^{-3}	4.68×10^{-3}	20	1.93×10^{-3}	1.99×10^{-3}

Table 6. MIV value and weight value of each influencing factor of conductor stability.

Influencing Factors	MIV Value	Weight Value/%
Sea state recurrence period	0.037	5.01
Seabed depth	−0.244	33.14
Soil properties	−0.063	8.62
Conductor material	−0.011	1.52
Mud entry depth	−0.022	2.97
Height of conductor wellhead	0.359	48.73

From Table 5, it can be seen that the prediction error of the trained prediction model based on the limit learning machine is small and meets the requirement on the prediction accuracy. From the MIV value of each influencing factor in Table 6, it can be seen that the sea state recurrence period, the conductor wellhead height, and the maximum displacement of the conductor shows a positive correlation, i.e., the larger their values, the larger the value of the conductor displacement; the mud line depth, soil properties, conductor material and the depth of mud entry show a negative correlation with the maximum displacement of the conductor, i.e., the larger the value of the influencing factor, the larger the value of the conductor displacement. The correlation analysis based on the ELM-MIV algorithm is consistent with the conclusions from the simulations and calculations in the previous sections. From the weight value of each influencing factor of the conductor stability, it can be seen that the factors affecting the stability of the conductor are, the conductor wellhead height, seabed depth, soil properties, sea state recurrence period, mud entry depth, and conductor material (in descending order).

5. Conclusions

- (1) Under the selected ultimate conditions, the ultimate displacement of the conductor is 0.5369 m, the ultimate angle of rotation is 2.699×10^{-2} rad, the ultimate bending moment is 210.2 kN-m, and the ultimate equivalent force is 14.23 MPa, which still meet the operational safety conditions and represent the advantages of RMR technology.
- (2) The lateral load of the external environment of the conductor is the major factor affecting the lateral stability of the conductor, so all stability parameters of the conductor will increase with the increase in the sea state recurrence period and the height of the conductor wellhead. Different natures of the seabed soil will lead to different soil resistance of the conductor, the harder the soil, the less the deformation. Conductor materials have too little effect on the conductor stability. As the depth of the conductor in the mud increases, the displacement and angle of rotation of the conductor gradually decrease, while the bending moment and equivalent force first increase and then decrease, with the displacement and angle of rotation increasing sharply when the depth of the conductor in the mud is 10 m.

- (3) Sea state recurrence period, conductor wellhead height, and the maximum conductor displacement show a positive correlation. Seabed depth, soil properties, conductor material, and driving depth showed a negative correlation with maximum conductor displacement. The weight values of sea state recurrence period, seabed depth, soil properties, conductor material, driving depth, and conductor wellhead height are 5.01%, 33.14%, 8.62%, 1.52%, 2.97%, and 48.73%, respectively. The factors affecting the conductor stability in descending order are conductor wellhead height, seabed depth, soil properties, sea state recurrence period, driving depth, and conductor material.

Author Contributions: Conceptualization, R.Q. and B.X.; Data curation, H.C. and Q.L.; Formal analysis, J.W. and Q.F.; Methodology, C.L. and X.L.; Project administration, R.Q. and B.X.; Software, L.W.; Writing—original draft, C.L. and R.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2021YFC2800802; 2021YFC2800803), Hi-tech Ship Project of Ministry of Industry and Information Technology (CJ05N20), Geological Survey Project of China Geological Survey (DD20221721; DD20211421), Guizhou Province Science and Technology Support Program (2022-245) and Geological scientific research project of Guizhou Provincial Bureau of Geology and Mineral Exploration and Development (2021-25).

Data Availability Statement: All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

γ_c	Unit effective capacity of the soil at depth x under the mud line, kN/m^2
C_u	Undrained shear strength of the soil, kPa
x	Depth, m
D	Diameter of the structure, m
ξ	Causeless empirical constant, 0.25–0.5, the soil is hard to take the small value
x_r	Turning point depth of the ultimate horizontal bearing capacity, m
P	Transverse ultimate soil resistance of the structure at the depth x below the mud line when the lateral displacement of the structure occurs, kPa
y	Transverse displacement of the structure at the depth x below the mud line, m
y_{50}	Transverse displacement of the structure when the soil transverse soil resistance is half of the ultimate transverse soil resistance, m
ε_{50}	Strain occurring at 1/2 maximum stress in the as-built soil undrained test, m
EI	Conductor bending stiffness
y	Conductor transverse deformation
z	Conductor down into the depth
p	Conductor subject to the transverse homogeneous soil resistance
f_c	Drag force per unit length of the structural member, N
ρ	Density of the fluid, kg/m^3
C_D	Drag force coefficient, 0–150 m below sea level to take 1.2, 150 m below sea level to the sea floor to take 0.7
D_C	Hydraulic outside diameter of the structural member, m
v	Velocity of the fluid at the point perpendicular to the structural member, m/s
f_l	Drag force per unit length of the structural members, N
C_M	Inertia force coefficient
$\frac{d_\mu}{d_t}$	Seawater motion at the calculation point generated by the water quality point acceleration perpendicular to the structural members, m/s^2
β	Weights of the implicit layer neurons and the output neurons
H	Implicit layer output matrix

T	Output layer matrix
w	Weights of input neurons and hidden layer neurons
b	Threshold of hidden layer neurons
i	Serial number of neurons
Y	Training target matrix
m	Number of samples
t	New output vector value obtained after adding or subtracting a quantity

Appendix A

Table A1. Input data of weight analysis based on ELM-MIV.

Number	Sea State Recurrence Period (year)	Seabed Depth (m)	Seabed Soil Properties	Conductor Material (Pa)	Driving Depth (m)	Conductor Wellhead Height (m)	Conductor Maximum Displacement (m)
1	1	10	1784066	1.9×10^{11}	40	7	1.01×10^{-2}
2	10	500	1784066	1.9×10^{11}	20	7	5.06×10^{-3}
3	1	1000	30156639	1.9×10^{11}	60	4	7.63×10^{-5}
4	5	150	1784066	1.5×10^{11}	80	9	3.79×10^{-2}
5	25	10	1784066	2×10^{11}	50	9	1.96×10^{-2}
6	25	200	30156639	1.9×10^{11}	90	9	3.87×10^{-3}
7	5	500	154022319	2.11×10^{11}	80	1	3.51×10^{-5}
8	1	100	30156639	1.5×10^{11}	70	6	8.48×10^{-4}
9	5	250	5752930	2.11×10^{11}	20	5	8.18×10^{-3}
10	1	50	1784066	2.11×10^{11}	10	2	2.01×10^{-3}
11	5	50	5752930	1.9×10^{11}	40	8	7.49×10^{-2}
12	5	150	154022319	1.9×10^{11}	90	8	6.59×10^{-3}
13	1	100	154022319	1.5×10^{11}	20	2	1.38×10^{-4}
14	10	50	30156639	2.11×10^{11}	50	7	8.94×10^{-3}
15	10	10	30156639	1.5×10^{11}	60	8	1.56×10^{-2}
16	1	500	154022319	2.11×10^{11}	30	9	5.90×10^{-4}
17	5	300	30156639	1.9×10^{11}	20	9	2.50×10^{-3}
18	25	50	5752930	1.9×10^{11}	80	4	3.63×10^{-2}
19	5	1000	154022319	1.5×10^{11}	10	9	1.03×10^{-3}
20	25	250	154022319	2×10^{11}	90	7	2.13×10^{-3}
21	25	1000	154022319	2.11×10^{11}	40	6	4.70×10^{-4}
22	1	200	5752930	2×10^{11}	20	4	1.99×10^{-3}
23	5	250	1784066	1.5×10^{11}	40	3	2.24×10^{-3}
24	1	100	5752930	2×10^{11}	40	9	1.13×10^{-2}
25	10	300	5752930	2.11×10^{11}	50	6	8.65×10^{-3}
26	25	250	30156639	2×10^{11}	60	1	7.93×10^{-5}
27	25	500	30156639	2×10^{11}	70	2	1.19×10^{-4}
28	1	500	5752930	1.9×10^{11}	90	3	7.05×10^{-4}
29	1	250	30156639	2×10^{11}	80	8	5.47×10^{-4}
30	1	250	30156639	1.9×10^{11}	50	2	4.35×10^{-5}

Table A1. Cont.

Number	Sea State Recurrence Period (year)	Seabed Depth (m)	Seabed Soil Properties	Conductor Material (Pa)	Driving Depth (m)	Conductor Wellhead Height (m)	Conductor Maximum Displacement (m)
31	10	250	154022319	1.9×10^{11}	10	6	1.36×10^{-3}
32	5	1000	30156639	2.11×10^{11}	30	7	4.15×10^{-4}
33	1	200	1784066	1.5×10^{11}	80	7	3.44×10^{-3}
34	25	1000	1784066	1.9×10^{11}	70	3	8.72×10^{-4}
35	25	100	1784066	2.11×10^{11}	50	8	5.29×10^{-2}
36	1	150	154022319	1.9×10^{11}	50	3	1.90×10^{-4}
37	10	150	5752930	2×10^{11}	70	7	2.08×10^{-2}
38	10	50	5752930	2×10^{11}	30	3	2.09×10^{-2}
39	25	200	30156639	1.5×10^{11}	30	6	1.78×10^{-3}
40	5	10	154022319	2×10^{11}	70	4	3.06×10^{-3}
41	1	1000	5752930	1.5×10^{11}	90	1	1.07×10^{-5}
42	1	10	1784066	2.11×10^{11}	10	1	2.00×10^{-3}
43	25	250	1784066	1.5×10^{11}	30	4	5.03×10^{-3}
44	5	1000	5752930	1.5×10^{11}	50	5	2.23×10^{-3}
45	5	200	30156639	2.11×10^{11}	70	8	2.17×10^{-3}
46	1	10	5752930	2×10^{11}	80	6	1.20×10^{-2}
47	25	50	30156639	2.11×10^{11}	20	1	4.39×10^{-4}
48	5	50	1784066	2×10^{11}	90	6	3.02×10^{-2}
49	10	300	1784066	1.9×10^{11}	70	1	5.70×10^{-4}
50	1	300	1784066	2×10^{11}	60	5	8.96×10^{-4}
51	10	1000	154022319	2×10^{11}	80	2	6.00×10^{-5}
52	5	200	154022319	2×10^{11}	50	1	7.56×10^{-5}
53	25	150	5752930	2.11×10^{11}	60	2	7.69×10^{-3}
54	10	100	5752930	1.9×10^{11}	30	1	4.76×10^{-3}
55	1	150	5752930	2.11×10^{11}	20	6	6.26×10^{-3}
56	10	200	1784066	1.9×10^{11}	40	2	1.60×10^{-3}
57	25	10	154022319	1.5×10^{11}	20	3	2.87×10^{-3}
58	25	150	1784066	2.11×10^{11}	30	5	1.99×10^{-2}
59	10	10	30156639	2.11×10^{11}	90	5	4.62×10^{-3}
60	10	1000	1784066	2×10^{11}	20	8	3.41×10^{-3}
61	10	300	30156639	2.11×10^{11}	80	3	2.88×10^{-4}
62	10	250	5752930	2.11×10^{11}	70	9	1.87×10^{-2}
63	10	500	154022319	1.5×10^{11}	50	4	4.10×10^{-4}
64	10	100	1784066	2.11×10^{11}	90	4	1.51×10^{-2}
65	1	300	154022319	2×10^{11}	30	8	4.64×10^{-4}
66	25	300	154022319	2.11×10^{11}	40	4	5.95×10^{-4}
67	5	500	1784066	1.9×10^{11}	60	6	3.11×10^{-3}

Table A1. Cont.

Number	Sea State Recurrence Period (year)	Seabed Depth (m)	Seabed Soil Properties	Conductor Material (Pa)	Driving Depth (m)	Conductor Wellhead Height (m)	Conductor Maximum Displacement (m)
68	10	50	154022319	1.5×10^{11}	60	9	2.26×10^{-2}
69	25	100	5752930	1.9×10^{11}	80	5	4.09×10^{-2}
70	5	150	30156639	2×10^{11}	10	4	1.39×10^{-3}
71	25	200	5752930	2.11×10^{11}	60	3	4.70×10^{-3}
72	5	100	154022319	1.5×10^{11}	60	7	8.64×10^{-3}
73	25	500	5752930	1.5×10^{11}	10	8	4.48×10^{-2}
74	5	10	5752930	1.9×10^{11}	30	2	1.19×10^{-2}
75	10	500	30156639	2×10^{11}	40	5	4.66×10^{-4}
76	1	50	154022319	1.5×10^{11}	70	5	5.86×10^{-4}
77	10	150	30156639	1.5×10^{11}	40	1	2.26×10^{-4}
78	10	200	154022319	1.9×10^{11}	10	5	1.06×10^{-3}
79	5	100	30156639	2×10^{11}	10	3	1.27×10^{-3}
80	5	300	1784066	1.5×10^{11}	90	2	1.26×10^{-3}
81	25	300	5752930	1.5×10^{11}	10	7	1.93×10^{-3}

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