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Analysis of Three-core Composite Submarine Cable Damage due to Ship Anchor

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ABSTRACT Suspended submarine cables are prone to likely mechanical damages due to ship anchors, which represent a significant threat to the reliability of power transmission and information communication networks. This paper is aimed at presenting a detailed investigation to the dynamic response of a ship anchor impacting the suspended section a submarine cable in order to reduce the risk of cable damage. In this regard, a three-dimensional and dual nonlinear model of the anchor affecting a subsea cable is established using ABAQUS finite element analysis software. The damage effect due to the ship anchor on the suspended and buried-in-soil sections of the cable is studied. Results show that when a ship anchor hits a suspended section of the subsea cable, the mechanical stress is concentrated at the impacted point and is progressing to both sides of the suspended section with a significant cable deformation. On the other hand, the buried section of the cable suffers from a short impact process, and the deformation is relatively small. To reduce this impact effectively, a detailed technical comparison of two common dumping and filling methods is conducted, and the better protection method is proposed.

INDEX TERMS Composite submarine power cable; anchor fall impact; suspended cable and pipeline; throwing method; dent depth

I. INTRODUCTION

Submarine cables have been used for decades and considered as the lifeblood of national energy. Modern composite submarine cables integrate multi functions of power transmission, information communication, and sensing [1-3]. Composite submarine cables have complex structures and work under harsh operating environment. Compared with traditional power and optical cables, they have higher failure rate and are prone to more types of faults [4-7]. Since the first successful laying of a submarine cable, external substances have constantly threatened and damaged these cables over the years. Once a submarine cable is seriously damaged, it results in catastrophic consequences including life threatening for human and aquatic animals along with substantial loss of revenue due to business interruption and cost of repair or replacement. Typical maintenance period of submarine cables is from 4 to 11 days, and the investment in operation and maintenance is as high as 10 million yuan[8]. This may lead to a delay in the

expected construction period and resulting in economic losses of 2 to 3 months [9-11]. The threats to submarine cables can be divided into human factors and natural factors, among which the main element of damage caused by human factors is the anchor damage, along with other biological factors that include geological collapses, faults, suspended and other uncertain factors [12-14].

Overhanging submarine cables are quite common. For example, of the 61 pipelines tested at Chengdao, 56 were suspended, posing a huge safety hazard to subsea pipeline projects [15]. The factors leading to overhanging submarine cables are numerous and include currents, the topographical environment of the seabed and construction factors. In addition, the presence of submarine cables and submarine structures can change the existing flow field, which can increase the velocity of currents and create vortices. Scouring and siltation result from the equilibrium of the hydraulic transport of sediment. If the velocity of the current is larger than the sediment initiation velocity of the seabed, the

seawater erodes the sediment by, which eventually causes the sea cable to become suspended. Secondly, the topography of the seafloor is itself uneven, so if there are alterations in the seafloor sand slope migration or extensive seabed erosion, it will intensify the suspension of the cable. Thirdly, it is not easy to prevent residual stresses in the cable laying construction. This causes local buckling and deformation of the submarine pipeline, or can even cause the cable to move in the horizontal plane, thus creating overhang [16].

It is common for submarine cables to be hung in the air, which increases risks to the cables than the direct impact of anchors. Overhanging of submarine cables can be due to marine environment and topology or during construction phase. During burial and because of the rough terrain and improper control of the cable laying speed, the submarine cable will be hung in the air, which imposes a significant mechanical stress on the cable. In addition, the complex structure of seabed along with ocean currents and waves may change the soil topology, leaving the submarine cables exposed and suspended on the surface of the seabed. Vortex-induced vibration and ocean currents accelerates the soil scouring impact, and the loose sediment increases the suspended length of the submarine cable, thereby increasing the probability of anchor damage [17-20]. The suspended submarine cables' force performance is severely affected, which makes them even more liable to many kinds of damage such as deformation, buckling, resonance and even fracture, with a result of considerable economic damage. The statistics of underwater pipeline crossing accidents in China in the last decade show that more than 80% of submarine pipeline accidents were caused by fracture damage subsequent to the pipeline being suspended [21]. Effective assessment to the risks of ship anchor damages to the suspended section of submarine cables is essential to improve composite cable design, enhance cable laying methods, and increase submarine cable protection.

A few research on the suspension of submarine cables and anchor damage can be found in the literature. Theoretical and experimental research has been conducted to investigate the mechanical behavior of submarine pipelines. Huang et al. [22] carried out a numerical simulation study for the impact of a suspended channel on an anchor. The paper analyzed the influence of the anchoring speed and concrete layer on the mechanical stress imposed on a submarine pipeline and used the coupling effect between the pipe and soil to reflect the seabed effect. Luo et al. [23] considered the interaction between the channel and the ground and employed the Docker-Prager model to simulate the seabed to analyze the dynamic impact on a submarine suspended pipeline due to a falling object. The paper also investigated the effect of volume parameters on the pipeline deformation and the amplitude of the dynamic response. Kouretzis et al. [24] considered materials' nonlinear impact and analyzed the buried pipelines' internal forces and strains under surface subsidence and uplift conditions. Kinash et al. [25] simplified

the thin-walled cylindrical pipe response problem under combined load and internal pressure into a one-dimensional model using the plastic theory of shell and thin-film. References [26, 27] compared and analyzed the stress of submarine pipelines in sandy and cohesive soils, respectively. Sudhan et al. [28] improved the effects of buried depth, relative slope height, and scattering parameters on the stress of fully buried submarine pipeline through experimental analysis. Reported results can provide a specific basis for the buried depth of submarine cables.

Up till now, research into buried submarine cables has been focused on towed anchors. The depth of the cable's burial is a key factor in preventing its damage from falling anchors and towing. The analysis should therefore include the function of the anchor in the soil. The literature [29] looks into the buried depth protection index of submarine cables, using a combination of physical model tests, numerical simulations and hypothetical analysis. The effects of anchor bottoming speed, sinking energy and anchor mass on the penetration depth of anchor rods are analysed. By establishing the anchor towing analysis model it is demonstrated that in the study area, the burial depth protection index of submarine cables is 3 metres. The literature [30, 31] conducted numerical replications of ship anchor incursion into soil to discover the effect of anchor movement on submarine cables. The conclusion was that it is possible that dragging under the soil can still cause damage to the submarine cable even if there is no direct contact between it and the ship anchor. This is due to the soil movement between the anchor and the submarine cable, and the sidewall pressure of the anchor which indirectly deepens the mechanical damage to the submarine cable.

Concerning the research on the protection process of suspended submarine cables, both domestic and overseas research largely focuses on the throwing and filling method and the bionic grass protection method. As the research object, the paper [32] uses the sandbag stacking form in the case of submarine cable suspension management in Bohai Sea, along with Fluent software to create a two-dimensional flow field model to analyse the distribution law of surrounding flow field under diverse forms of sandbag stacking, to decrease the likelihood of sandbags being washed away by water movement. In the paper [33] the rockfill-anchor-cable discrete element model was constructed on the PFC3D simulation platform. Quantitative evaluation of the resistance of submarine cables to anchorage damage and simulation of the mechanical properties of the rock throw protection layer throughout local lateral intrusion of the anchor rods to present a foundation for the protection of anchor rods from rock throw protection. The literature [34], shows the velocity field distribution of bionic aquatic grass along the vertical plane is measured using typical particle image velocimetry (PIV). It concluded that the method of bionic grass protection is effective in suppressing the speed

of the water and decreasing the likelihood of overhanging the submarine cable pipe.

While some studies on the dynamic behavior of submarine pipelines can be found in the literature, as discussed above, not much attention was given to analyze the dynamic response of submarine composite cables due to ship anchor. This, the main contribution of this paper is to present a detailed analysis to the dynamic response of a three-core AC composite submarine cable due to ship anchors. In this regard, a three-dimensional dual nonlinear finite element model of anchor-submarine cable-soil is established using ABAQUS software tool. Simulation is conducted for two environmental conditions surrounding the suspended and buried-in-soil sections of the cable. The structural stress, strain, and possible damage of the three-core composite submarine cable due to ship anchor under different environments are analyzed. In addition, specific protection measures are proposed for the suspended section. Also, the protective effect of the submarine cable from dropping anchors under other throwing and filling methods is studied.

II. THEORETICAL ANALYSIS AND METHODS

A. COMPOSITE SUBMARINE CABLE STRUCTURE

The three-core submarine cable structure can be divided into two parts: a twisted clockwise module that includes an insulating layer, conductor, cylinder and optical fiber unit, and the other part is a counterclockwise helical member of the armored layer outside the filling. The YJQF41-26/35-3×500+2×36C submarine cable (including 72-core optical cable) is selected as the research object. The physical parameters and structure configuration of this cable are shown in Table 1 and Figure I respectively.

TABLE I
STRUCTURE PARAMETERS OF SUBMARINE CABLES

Number	Material name	Thickness (mm)	Outer diameter (mm)
1	Water-blocking copper conductor	-	26.5
2	Conductor screen	1.0	28.5
3	XLPE insulation	8.0	44.5
4	Insulation screen	1.0	46.5
5	Semiconductor water-blocking tape	0.5	47.5
6	Alloy lead sheath	2.1	51.7
7	Anti-corrosive	0.2	52.1
8	Polyethylene sheath	1.8	55.7
9	Polypropylene filling layer	-	-
10	Wrapping tape	0.6	121.2
11	Inner bedding	1.3	124.1
12	Steel wire armoring	6	136.6
13	Outer serving	3.4	143

14	Fiber optic sheath	2.2	12.4
15	Outer wire	1.0	8.0
16	Inner wire	1.5	6.0
17	Stainless steel Tube	-	3.0
18	Fiber and fill	-	-

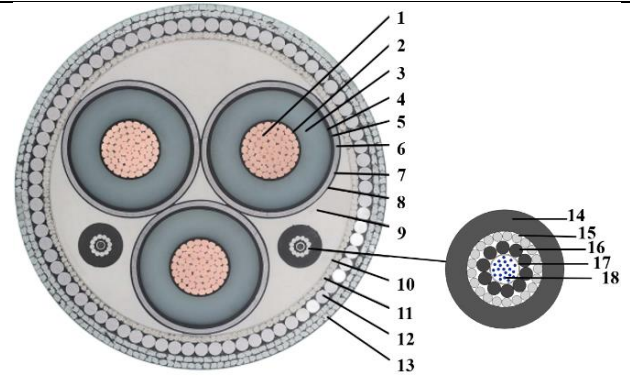


FIGURE 1. Typical structure of three-core AC composite submarine cable

B. DROP ANCHOR THEORY ANALYSIS

When the anchor drops into the water, gravity initially accelerates the anchor. The drag on the anchor then increases and after reaching a certain depth, the anchor speed stabilizes. When the anchor penetrates the soil, the resistance of the earth first increases and then decelerates to zero.

The anchor is assumed to have a height above the water surface and an initial velocity of 0. Moreover, it does not consider the reduction in chain-out speed, wind load, and wave factor that the anchor machine reduces. Then the anchor's free-fall kinetic equation in seawater can be written as:

$$mg - \rho_w Vg - \frac{1}{2} \rho_w C_D A v^2 = m \frac{dv}{dt} \quad (1)$$

When the anchor is released at a height H above the water surface, the speed of the incoming anchor is $v = (2gH)^{1/2}$. The velocity of the descent to a water depth of l is:

$$v = \sqrt{2gH + \frac{2Vg(\rho_a - \rho_w)}{C_D \rho_w A} \times \left[1 - \exp\left(-\frac{\rho_w C_D A l}{V \rho_a}\right) \right]} \quad (2)$$

where m is the mass of the anchor, ρ_w is the density of the seawater, V is the discharge volume of the anchor, C_D is the drag coefficient, A is the retaining water area of the front face of the anchor, v is the anchor speed, ρ_a is the density of the anchor.

The equilibrium velocity is:

$$v_t = \sqrt{\frac{2Vg(\rho_a - \rho_w)}{C_D \rho_w A}} \quad (3)$$

The bottoming kinetic energy of the anchor is:

$$E_k = \frac{1}{2} m v^2 \quad (4)$$

Newton's second law equation for the anchor in the inlet section is:

$$F_s - mg = m \frac{dv}{dt} \quad (5)$$

The resistance of the soil is related to the quality of the earth. According to [35], the resistance of sandy and clay soils can be respectively calculated from:

$$F_{s1} = 0.5N_\gamma \gamma' BA + N_q p_0 A \quad (6)$$

$$F_{s2} = (N_c (C_{u0} + kh) + p_0) A \quad (7)$$

where $p_0 = \rho gh$, the overlying soil pressure.

If the anchor penetrates the soil to a depth of h , the energy consumed by the anchor in penetrating the ground can be obtained by integrating the soil resistance:

$$E_a = \int_0^h F_s dh \quad (8)$$

The energy consumed by the anchor due to resistance in the through-soil section in sandy and clay soils, can be respectively calculated from:

$$E_a = 0.5N_\gamma \gamma' BA h + 0.5N_q \gamma' A h^2 \quad (9)$$

$$E_a = N_c C_{u0} A h + 0.5(\gamma' + N_c k) A h^2 \quad (10)$$

where C_{u0} is the undrained shear strength of the mud surface, k is the rate of change along with the depth, N_q , N_r , and N_c are the fill material bearing capacity coefficients, γ' is the adequate capacity of the fill material per unit mass in kN/m^3 , B is the anchor crown width, and h is the depth of entry.

The impact energy of the anchor through the water and earth, in contact with the submarine cable, E_c is:

$$E_c = E_k - E_a \quad (11)$$

When the burial depth is large enough, E_a is greater than E_k , and the cable will not be damaged. The impact energy will likely collapse the submarine cable in case of shallow burial depth.

III. ANCHOR DAMAGE FINITE ELEMENT CALCULATION

A. SUBMARINE CABLE MODEL CONSTRUCTION

It is necessary to model the system in layers to build the structure of the submarine cable. Firstly, SolidWorks is used to draw a plan, stretch and twist, to finally forming an assembly. The three-core water-blocking copper conductor must be 120° symmetrical. The outer layer of the conductor is wrapped with an XLPE insulating layer and an alloy lead sheath. The optical unit is in the middle of two adjacent conductors and twisted clockwise. The filled construction utilizes a combination of cylinder and inner helical component. The outer armor is made of galvanized steel balls spirally counterclockwise with a winding angle of 10° . At the same time, the outer layer is wrapped by a polypropylene (PP) layer. The submarine cable model diagram is shown in Figure 2.

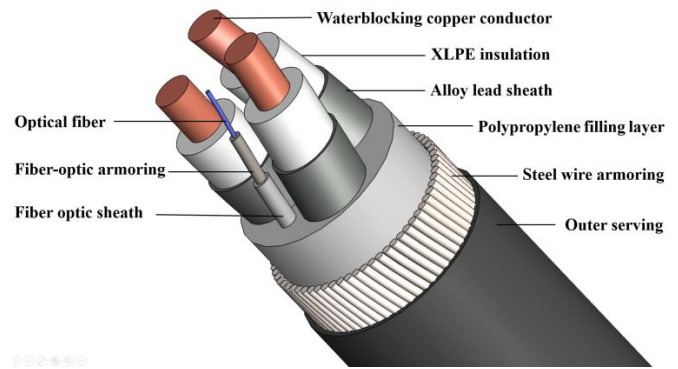


FIGURE 2. Simplified model of submarine cable

B. MODEL OF ANCHOR HITTING SUSPENDED SUBMARINE CABLE

The submarine cable is laid under the soil. After a long period of complex sea conditions, the ground is washed away by waves, and currents, and the submarine cable is gradually exposed and suspended. As shown in Figure 3, the floating phenomenon occurs in actual projects. At the junction of the suspended section and the buried-in-soil section, the seabed level is uneven, and the soil is loose, which will increase the length of the suspended section of the cable in the long run.

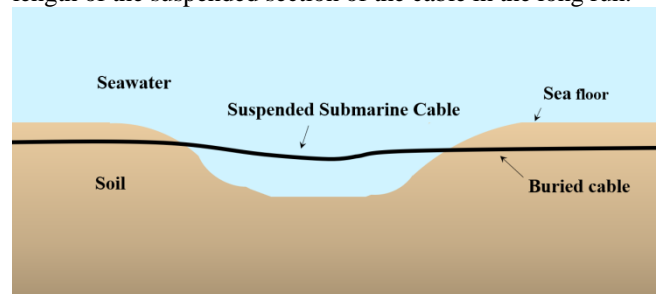


FIGURE 3. Schematic diagram of the suspended submarine cable

The impact of the anchor on the submarine cable is a transient dynamic process involving complex nonlinear and contact problems. The model calculation is completed using the dynamics module Explicit in ABAQUS software. The suspended section of the submarine cable is modelled by simulating a concave broken soil model centered by the submarine cable with a suspended height of twice the outer diameter. As shown in Figure 4, the submarine cable spans a kilometer long, which is long enough compared to the impact site, and the soil and submarine cables at both ends are set to be fixed to constrain the displacement in the X, Y, and Z directions. The anchor exerts an initial vertical velocity and is assumed to hit the submarine cable in the suspended section. The soil adopts the Mohr-Coulomb model to construct its ideal elastic-plastic deformation under impact load.

For the contact setting, the mechanical behavior of the tangent and the contact surface is described with the help of penalty function. Each contact surface is allowed to slip so that the contact relationship between the anchor contact surface, the submarine cable surface, and the seabed surface is established assuming a corresponding friction coefficient

of 0.33. The internal structure of the submarine cable is complicated, and a general contact is established to avoid penetration.

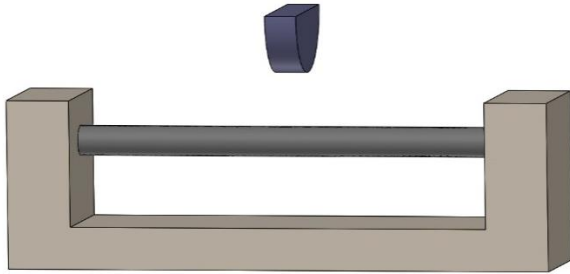


FIGURE 4. Finite element model of the submarine power cable impacted by a falling anchor

IV. NUMERICAL ANALYSIS

A. ANCHOR STATUS

When the anchor hits the submarine cable, the real impact can be judged by the state of the anchor. For comparison, when the anchor hits the submarine cable in the suspended section and the buried soil section, the speed-time history diagram of the anchor is as shown in Figure 5.

The anchor fell from the same position at a speed of 8 m/s. For the suspended section, the anchor has not contacted the cable body during the period of 0 ms to 4 ms, and it fell at a constant speed. After 4 ms, the ship anchor collided with the submarine cable with a rapid rate. When it is lowered, the anchor's kinetic energy and gravitational potential energy are gradually converted into the internal energy of the collision. Observing the buried soil section, the anchor falls directly in contact with the soil, and the anchor speed drops rapidly from its constant value during the period 0 ms to 4 ms, and with a rate close to zero after 4 ms. The comparison shows that the soil can effectively slow down the impact speed of the anchor and absorb a considerable amount of the energy.

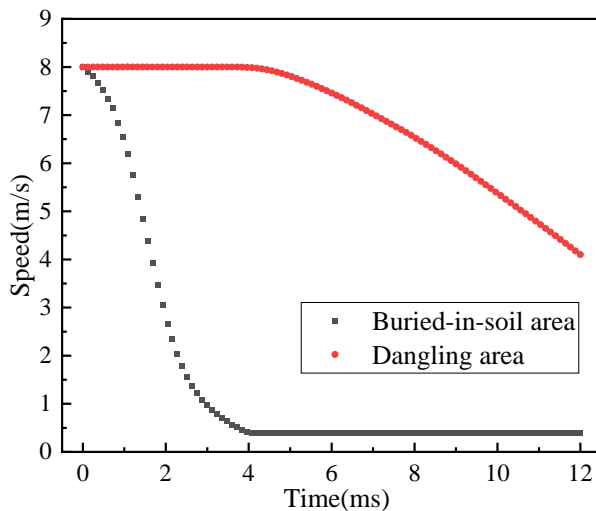
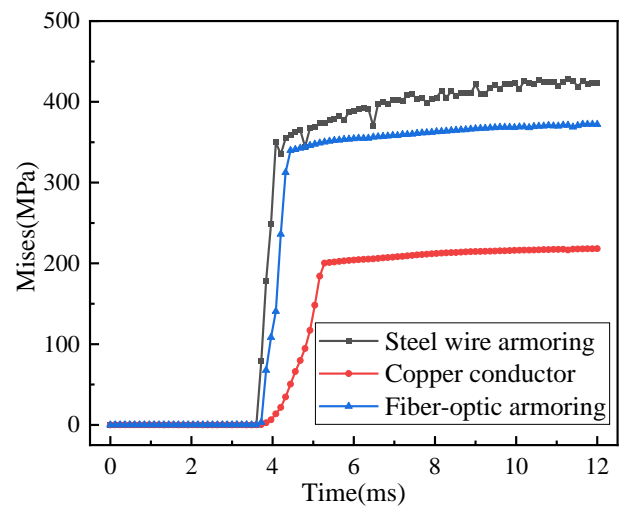


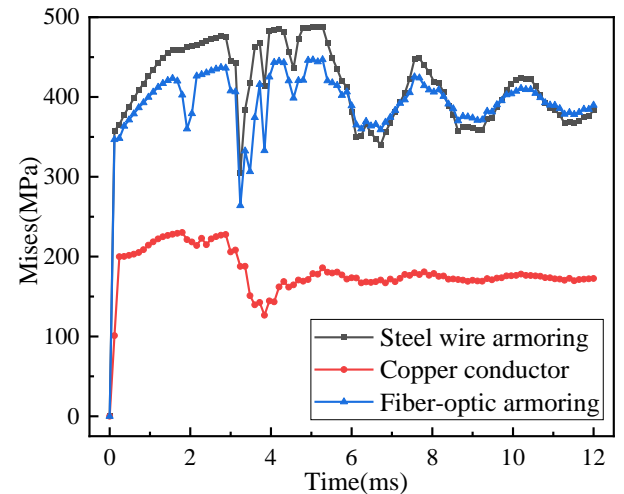
FIGURE 5. Anchor speed-time history diagram

B. SUBMARINE CABLE STRUCTURAL STRESS

At the same speed and height, the anchor hits the submarine cable in the suspended and buried soil sections. The equivalent stress of the outer armor layer, copper conductor, and fiber armor layer of the submarine cable at the maximum pressure is shown in Figure 6. The outer armor layer is the essential structure for external damage defense and bears the most forces to resist external damage compared to other layers. The copper conductor is the main power transmission component, and the yield stress parameter is smaller than the steel structure. Copper is located in the innermost layer of the submarine cable structure, and hence, its equivalent imposed stress is the smallest among the three layers. Optical fiber armor is a crucial structure to protect the broken core of the optical fiber. Optical fiber is responsible for communication transmission and monitoring the temperature and stress on the cable in real-time. The material of optical fiber armor is the same as that of the outer armor: galvanized steel. Since the optical unit is internally spiraled with the copper, the impact angle of the optical fiber armor varies significantly, but it is always inside the outer armor, and its equivalent stress is close to but consistently lower than the outer armor.



(a) Dangling area



(b) Buried-in-soil area

FIGURE 6. Stress-time history for each layer of the submarine cable

Figure 6(a) shows the equivalent stress-time history of the submarine cable when the anchor under the suspended section hits the submarine cable. From 0 ms to 4 ms, the anchor has not yet contacted the cable body, and the equivalent stress is zero. After 4 ms, the two collide and deform elastically, the equivalent stress increases linearly, and the armor and copper are close to the yield stress of their respective materials. After each layer structure reaches the yield stage, it enters the plastic stage. When the anchor hits the suspended section of the submarine cable, the speed of the anchor does not drop immediately due to its inertia, and the energy transmitted to the submarine cable is relatively low, so the entire impact process is slow.

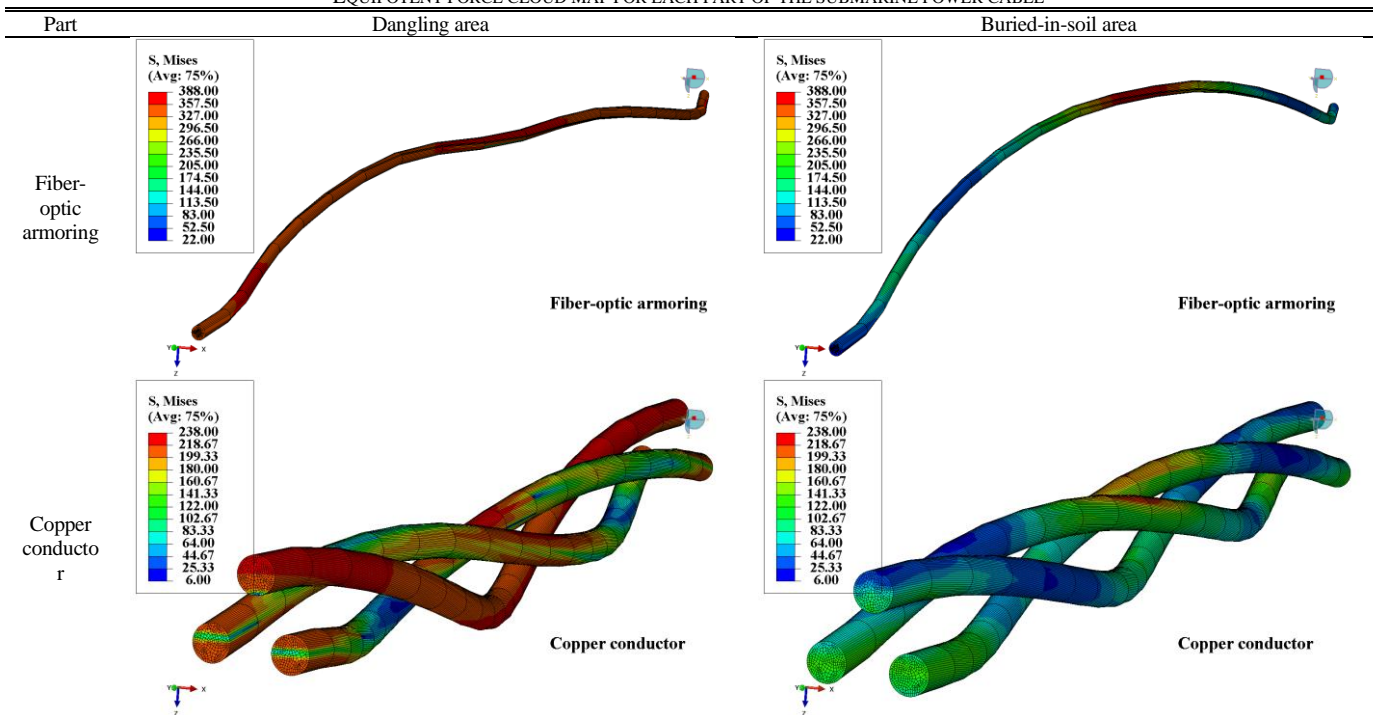
Figure 6(b) shows the equivalent stress-time history of the same three layers for the submarine cable in the buried-in-soil section. It can be seen from the figure that the elastic stage occurs within 0~0.2 ms, and the yield stress is quickly reached after which the maximum yield stress exceeds to enter the plastic stage. After 5 ms, the equivalent pressure on each layer structure fluctuates with gradually decreased amplitude due to the influence of the overall damping.

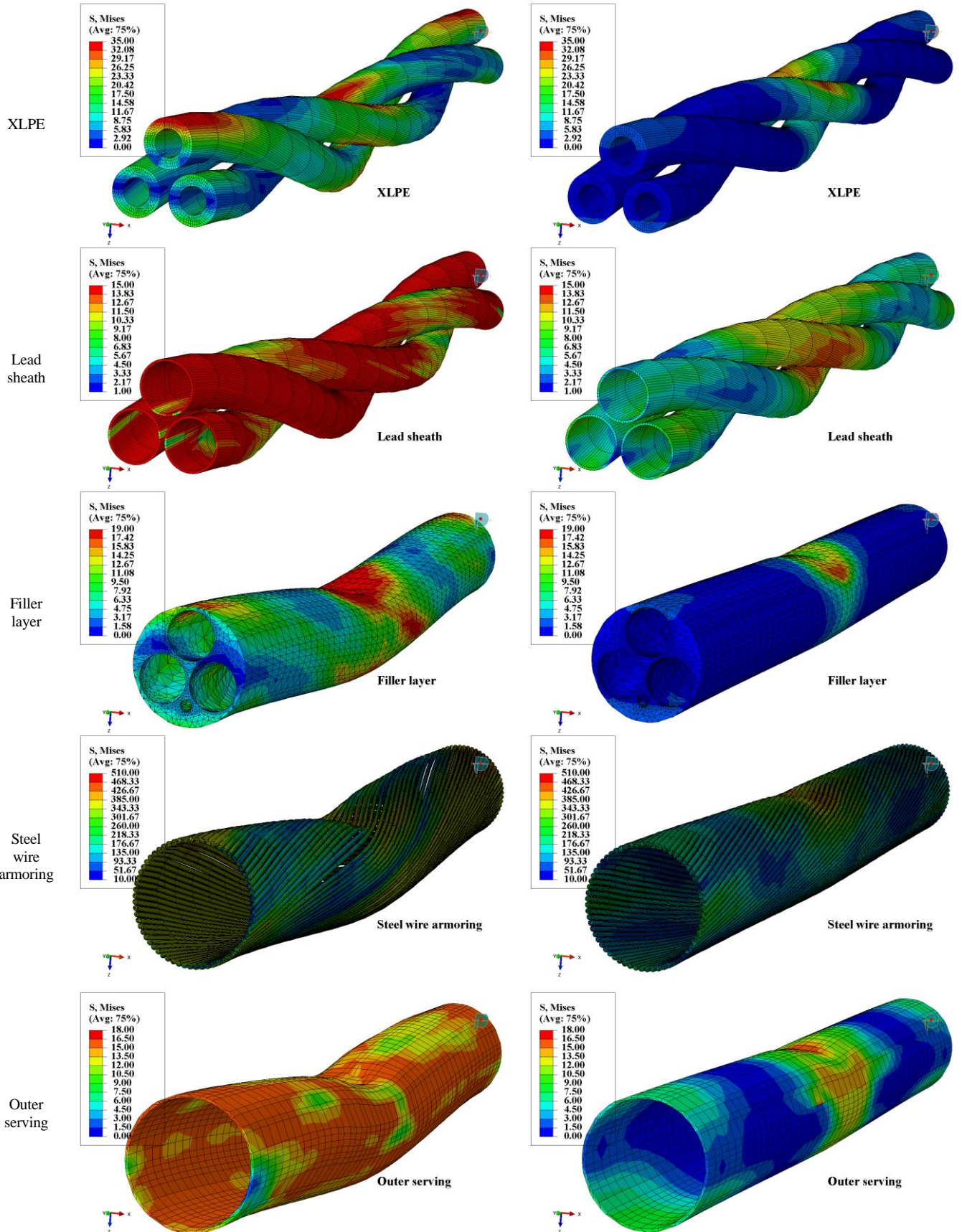
When the anchor hits the submarine cable under different environmental conditions (suspended and buried sections), the simultaneous equivalent stress on each layer structure of

the submarine cable is as shown in Table II. The layers shown in the cloud map are respectively the fiber-optic armoring, copper conductor, XLPE insulating layer, lead sheath, filler layer, steel wire armoring, and outer serving. Legend S describes the equivalent stress distribution of Mises.

Comparing dangling area and buried-in-soil area, the most intuitive observation is that in the suspended section environment, each layer's stress distribution is more uniform, and the concave deformation is more extensive. Moreover, the stress is concentrated at both the impact point, and the suspended section ends. In the buried soil section, the pressure is focused only on the local area where the anchor hits, and the depression deformation is small. In the same way, the force is transmitted to the torsion direction of the structure, which can effectively reduce the local damage at the impact point. During the entire impact process, the impact site is bent under the action of a substantial load, and the axial bending moment exerts compressive stress. Under internal pressure, the hoop stress generated by the outer armor is transmitted to the radial direction, and the adjacent filling is squeezed, which drives the internal deformation. The soil absorbs a considerable amount of the energy, so the suspended section is seriously deformed when it is hit by the anchor, which is more likely to threaten the operation of the submarine cable.

TABLE II
EQUIPOTENT FORCE CLOUD MAP FOR EACH PART OF THE SUBMARINE POWER CABLE





C. SUBMARINE CABLE STRUCTURAL SECTION DEFORMATION

Figure 7 shows a cloud diagram of the deformation of the submarine cable section at the impact point under different environmental conditions. As shown in Figure 7(a), in the suspended section, the outer sheath of the submarine cable and the outer armor have been peeled off from each other. Also, the outer sheath of the optical unit and the fiber armor are extruded from each other, and the lead sheath outside the copper conductor is squeezed out from the XLPE Layers. As shown in Figure 7(b), for the buried-in-soil section, the submarine cable's outer sheath and outer armor are squeezed and deformed, while the internal structure is almost intact. These results reveal that when anchors hit the suspended section of the cable, it is easy to lose the ability to protect the inner core of the submarine cable, which results in a significant deformation of the cross-section of the cable body, and the conductor power is significantly attenuated.

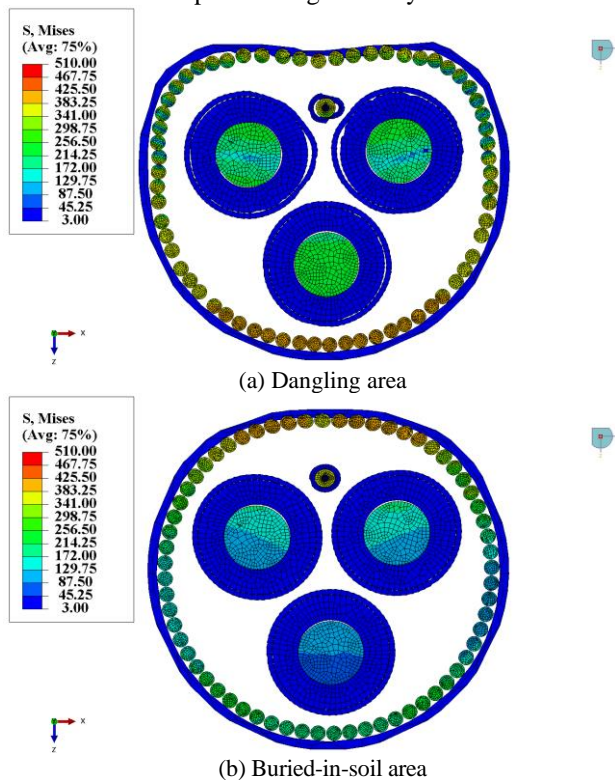


FIGURE 7. Deformation cloud map of submarine cable sections

V. MANAGEMENT OF SUBMARINE CABLES IN SUSPENDED SECTIONS

The typical suspended section adopts the throwing method to prevent the submarine cable from being mechanically damaged. The main throwing and filling methods include the throwing and filling sandbag method and the throwing and filling gravel method. The advantages and disadvantages of these two methods are listed in Table III. The two methods are simulated using finite element analysis by adding the material of the sandbag and gravel methods to the suspended area of the cable. The original parameters used in the above

simulation analysis are changed to simulate the anchor damage effect after employing throwing and filling method.

TABLE III

ADVANTAGES AND DISADVANTAGES OF THE THROW-AND-FILL METHODS

Method	Advantage	Disadvantage
Sandbag method	Simple process, convenient construction, does not affect production	It causes secondary suspension, and the reliability is low
Gravel method	Suitable for treating large-suspension spans, and the formed stone dam prevents the cable from being directly scoured by the ocean current.	There will be a dyke effect, the seabed at the bottom of the dyke will be easily hollowed out, and the rocks will settle.

Generally, the dent value of the submarine cable is used to evaluate the damage. As shown in Figure 8, when a certain mass shoots down the submarine cable at a certain speed, the entire submarine cable will have an irreversible dent depth. The change in the outer layer deformation is called the dent value: the larger the dent value, the more severe the damage. When the ratio of the dent value to the outer diameter of the submarine cable exceeds 5%, it will threaten the submarine cable's mechanical properties, power transmission, and communication functions.

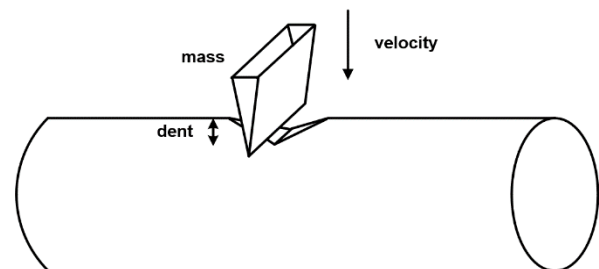


FIGURE 8. Dent prediction model

A. ANCHOR SPEED

Figure 9 shows the effect of anchor speed on the dent value when a 2000 kg anchor hits the submarine cable that employs throwing sandbags and gravel methods at its suspended section. When the anchor speed is less than or equal to 2 m/s, the sandbag and gravel methods result in similar cable's dent value.

Because the impact velocity is small at this time, the influence of soil characteristic is not a decisive factor. With the increase of the anchor speed, the dent value of the submarine cable increases exponentially. Because the anchor's speed increases and its mass is constant, the energy of the anchor will increase by the square of the speed. Comparing the two filling methods, the anchor damage of the submarine cable is more serious in sandbag environment. With the increase in speed, the protective effect of the sandbag and gravel environments becomes more different. While the elastic modulus of sandbags is low, the elastic modulus of gravel can reach more than 100 MPa. The rock and soil have a large elastic modulus and high hardness. Thus, the rock and dirt are more likely to reduce the speed of the

impact point, thereby absorbing the impact energy and can effectively buffer the mechanical damage caused by the anchor. The gravel-fill method is then preferred to reduce the risk of anchor damage near nautical areas.

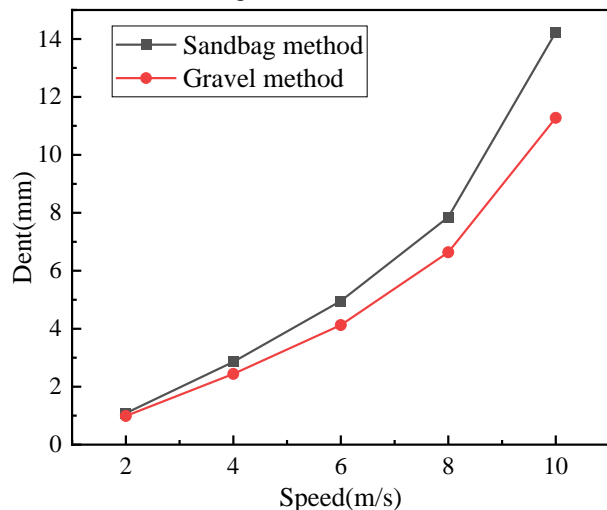


FIGURE 9. Relationship between anchor speed and dent value

B. ANCHOR WEIGHT

Figure 10 shows the relationship between the anchor mass and the dent value when the anchor hits the submarine cable at a speed of 10 m/s under different throwing and filling methods. As the anchor mass increases, the cable sag value also increases. However, as the anchor mass rises, the sag value's growth rate decreases, which is opposite to the influence of anchor speed on submarine cable damage. By observing the change of the sag value under the two throwing and filling methods, it is concluded that the protection effect brought by the throwing and filling gravel method is better than that of the throwing and filling sandbag method. When the anchor mass is 400 kg, the difference between the sag values of the two methods is slight (0.5327 mm). When the anchor mass is 2000 kg, the sag value difference between the two methods is 1.5544 mm. With the increase of anchor quality, the difference in sag values between the two methods keeps increasing. Therefore, when the anchor mass is more significant, and the damage to the submarine cable is more serious, the protective effect of the gravel filling method on the submarine cable is more pronounced. In the two throw-and-fill environments, the larger the parameters of the anchor mass and the anchor speed, the more significant the protection gap of the throw-and-fill method.

C. BURIED DEPTH

Figure 11 shows the relationship between the buried depth and the damage to the submarine cable is established for the 2000 kg ship anchor hitting the submarine cable at a speed of 10 m/s under different soil filling environments. The burial depth (D) shown in the figure is measured as multiple of the outer diameter of the submarine cable. The sag value of the submarine cable decreases with the increase of the buried depth. When the burial depth of the submarine cable is 1.8

times the outer diameter, the damage is almost reduced to zero. The soil in the sandbag environment is more likely to sag when it is impacted than in the gravel environment, and the soil environment with a lower elastic modulus has less influence on the impact of the anchor. Likewise, the shallower the burial depth, the more significant the difference between the sag values of the two methods. When the burial depth exceeds 1.5 times the outer diameter, the dent values in the two throw-fill environments remain the same. Generally speaking, the difference between the dumped soil and the buried depth is slight, and the buried depth has a more apparent protective effect on the submarine cable, which is much more critical than the dumped environment. Consequently, when the floating submarine cable is abandoned and filled, it is necessary to focus on the buried depth of the submarine cable under the dumped soil.

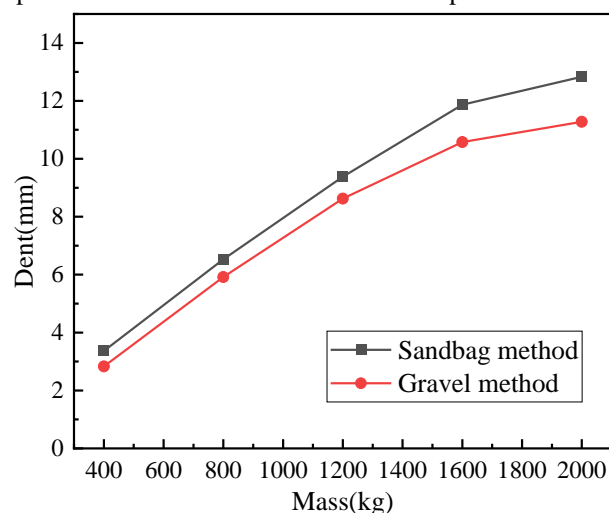


FIGURE 10. Relationship between anchor mass and dent value

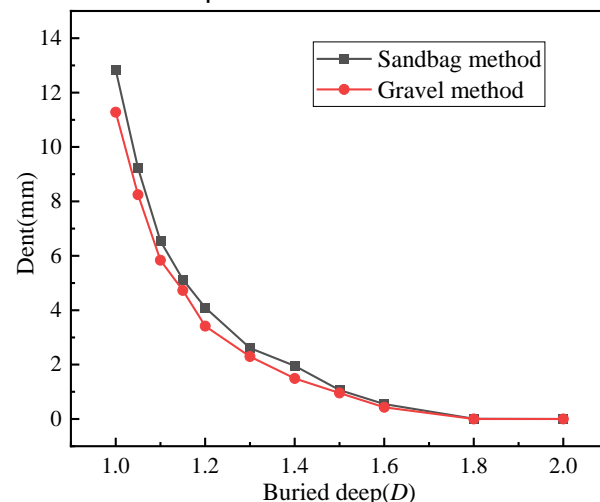


FIGURE 11. Relationship between buried depth and dent value

VI. CONCLUSION

Based on the finite element analysis software ABAQUS/Explicit, this paper simulates the impact of ship

anchors on the suspended section of a submarine cable. The paper also compares and analyzes the effect of the discontinued area and the buried soil section. The following conclusions are drawn:

- 1) Compared with the buried soil section, when the anchor hits the suspended area, the impact process is longer, and the time for the structure of the submarine cable to change from the elastic to the plastic stages is also longer.
- 2) By comparing the stress-strain programs of the suspended section and the buried soil section, it is concluded that in the broken section environment, the plastic deformation caused by the impact of the anchor on the submarine cable is more serious, and the stress is mainly concentrated at the impact position and on both sides of the suspended section. The plastic deformation of the buried-in-soil section is small, and the stress is concentrated at the impact point.
- 3) The dumping and filling method is adopted to treat the suspended section. The study found that the more serious the damage to the submarine cable, the more pronounced the gap between the protective effect of the throwing and filling sandbag method and the throwing and filling gravel method.
- 4) In the case of the throwing and filling gravel method the dent values of the cable are smaller than those found from the throwing and filling sandbag method and thus provide better protection than the latter method.
- 5) In this paper, the numerical analysis of the anchoring impact of submarine cables under the suspended section is established and only the effect of falling anchors is considered. Models for dragging anchors and hooking conditions can then be analyzed in future studies.

REFERENCES

- [1] H. Zhang, "Development prospects of high economy XLPE insulation HVDC submarine cable," *The 10th Renewable Power Generation Conference (RPG 2021)*, 2021, pp. 1046-1055, DOI: 10.1049/icp.2021.2223.
- [2] S. Kamran, L. Harnefors, H. P. Nee, S. Norrga, R. Teodorescu, "MMC - HVDC transmission technology and MTDC networks," *In Design, Control, and Application of Modular Multilevel Converters for HVDC Transmission Systems*, IEEE, 2016, pp.336-372, DOI: 10.1002/9781118851555.ch10.
- [3] Z. Lei, X. Huang, T. Liu and Y. Xu, "Analysis of an accident caused by current mismatch in the grounding structure of a high-voltage single-core submarine cable," *2021 IEEE 4th International Electrical and Energy Conference (CIEEC)*, 2021, pp. 1-5, DOI: 10.1109/CIEEC50170.2021.9510303.
- [4] K. Hicke and K. Krebber, "Towards efficient real-time submarine power cable monitoring using distributed fibre optic acoustic sensors," *2017 25th Optical Fiber Sensors Conference (OFS)*, 2017, pp. 1-4, DOI: 10.1117/12.2267474.
- [5] W. Mei, W. Pan, T. Chen, G. Song and J. Di, "Research and design of DC500kV optical fiber composite submarine cable," *2017 4th IEEE International Conference on Engineering Technologies and Applied Sciences (ICETAS)*, 2017, pp. 1-6, DOI: 10.1109/ICETAS.2017.8277901.
- [6] H. Takeshita, "First demonstration of uncoupled 4-core multicore fiber in a submarine cable prototype with integrated multicore EDFA," *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, 2022, pp. 1-3.
- [7] Z. Li, W. Jiang, A. Abu-Siada, "Research on a composite voltage and current measurement device for HVDC networks," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 9, pp. 8930-8941, Sept. 2021, DOI: 10.1109/TIE.2020.3013772.
- [8] D.X. Ji, J. L. Zhou, J. H. Qian, "Current development review of submarine cable detection methods," *Southern Power System Technology*, vol.15, no.5, pp. 36-49, Dec. 2021.
- [9] S. H. Wang, L. B. Yan, T. Li, "Key problems of design for AC 500 kV cross-linked polyethylene insulation submarine cable," *High Voltage Apparatus*, vol.8, no.54, pp. 225-230+236, Aug. 2018.
- [10] A. M. Ardelean, P. Minnebo. *HVDC Submarine Power Cables in the World*. 2015, pp. 20-45.
- [11] F. Xia, "Molecule diffusion behaviors of waterproof glue into silicone rubber insulation of submarine cable joints base on molecular dynamic simulation," *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, 2020, pp. 1-4, DOI: 10.1109/ICHVE49031.2020.9279993.
- [12] S. Xu, X. Xie and H. Huang, "Fatigue failure analysis and simulation calculation of submarine suspended pipelines," *OCEANS 2021: San Diego - Porto*, 2021, pp. 1-10, DOI: 10.23919/OCEANS44145.2021.9705899.
- [13] Q. Ren, H. Zeng and Z. Jiao, "Stability analysis of seabed suspended span pipeline under wave action," *2021 7th International Conference on Hydraulic and Civil Engineering & Smart Water Conservancy and Intelligent Disaster Reduction Forum (ICHCE & SWIDR)*, 2021, pp. 1540-1545, DOI: 10.1109/ICHCESWIDR54323.2021.9656453.
- [14] M. Wang, J. Wu and X. Wang, "Study on the critical nondeposit velocity in slurry pipeline based on suspended load energy consumption theory," *2016 Chinese Control and Decision Conference (CCDC)*, 2016, pp. 3970-3973, DOI: 10.1109/CCDC.2016.7531678.
- [15] L. J. Wang, J. K. Liu, "The scouring span and its control methods for subsea pipeline in Chengdao oil-field," *OGST*, vol. 1, no.44, pp. 44-48+61-65, Jan. 2004.
- [16] Arya, A. Kumar and B. Shingan. "Scour-mechanism, detection and mitigation for subsea pipeline integrity," *International journal of engineering research and technology*, May.2012.
- [17] Y. H. Cheng, "RETRACTED ARTICLE: Monitoring method based on GIS for submarine cable fault data," *Arabian Journal of Geosciences*, vol.14, no.6, pp.490, March.2021, DOI:10.1007/s12517-021-06717-z.
- [18] X. Du, X. L. Zhang, "Influence of ocean currents on the stability of underwater glider self-mooring motion with a cable," *Nonlinear Dynamics*, vol. 99, pp. 2291-2317, Dec. 2020, DOI:10.1007/s11071-019-05429-0.
- [19] A. Chen, Q. Wang, Z. Chen, "Investigating pile anchor support system for deep foundation pit in a congested area of Changchun," *Bull Eng Geol Environ*, vol. 80, pp. 1125-1136, Oct. 2020, DOI:10.1007/s10064-020-01985-7.
- [20] Y. Zhao, L. Wu, "Experiment on the behavior of a self-anchored suspension and cable-stayed hybrid bridge during structural transformation," *KSCE J Civ Eng*, vol. 24, pp. 1821-1831, March. 2020, DOI:10.1007/s12205-020-0881-9.
- [21] S. J. Li, Q. Q. Duan, H. Zhang, "Mechanical behaviors of protection cables installed on free-spanning pipelines in floods and its installation program," *Natural Gas Industry*, vol. 2, no.36, pp. 102-109, Feb.2016.
- [22] X. G. Huang, F. Sun, "Application of ANSYS/LS-DYNA in dynamic simulation of submarine pipeline impacted by an anchor," *China Offshore Platform*, vol. 5, no. 27, pp. 41-44. 2012.
- [23] M. Lou, H. Q. Ming, "The dynamic response analysis of submarine suspended pipeline impacted by dropped objects based on LS-DYNA," *Marine Science Bulletin*, vol.1, pp. 113-120, 2015.
- [24] G. P. Kouretzis, D. K. Karamitros, Sloan S W, "Analysis of buried pipelines subjected to ground surface settlement and heave," *Canadian Geotechnical Journal*, vol. 8, no. 52, pp. 1058-1071, 2015.

- [25] O. Kinash, M. Najafi, "Large-diameter pipe subjected to landslide loads," *Journal of Pipeline Systems Engineering & Practice*, vol.1, no. 3, pp. 1-7, 2012.
- [26] W. Magda, "Wave-induced cyclic pore-pressure perturbation effects in hydrodynamic uplift force acting on submarine pipeline buried in seabed sediments," *Coastal Engineering*, vol. 2, no. 39, pp. 243-272, 2000.
- [27] A. V. Kumar, S. Neelamani, S. N. Rao, "Wave interaction with a submarine pipeline in clayey soil due to random waves," *Ocean Engineering*, vol. 13, no. 32, pp. 1517-1538, 2005.
- [28] C. M. Sudhan, V. Sundar, S. N. Rao, "Wave induced forces around buried pipelines," *Ocean Engineering*, vol.5, no. 29, pp. 533-544, 2002.
- [29] X. Zheng, Y. Ge, Z. Lu, C. Cao, P. Zhou, S. Li, J. Chen. "Study on buried depth protection index of submarine cable based on physical and numerical modeling," *Journal of Marine Science and Engineering*, vol. 2, no. 10, pp. 137, Jan. 2022. DOI:10.3390/jmse10020137.
- [30] J. Grabe, "Penetration of ship anchors and the influence of submarine cables," *Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*, vol.9, no. 37, pp. 17-22, Sept. 2018, DOI: 10.1115/OMAE2018-78314.
- [31] O. David, "Impact on submarine cables due to ship anchor – soil interaction," *geotechnic*, vol.4, no.40, pp. 265-270, Dec. 2017, DOI: 10.1002/gete.201600027.
- [32] Y. Zhu, H. Yang, Y. Liu, "Numerical simulation of the combined slope protection effect of living stump and bamboo anchor," *Geotech Geol Eng*, vol.2, no. 40, pp. 635-645, Feb. 2022, DOI:10.1007/s10706-021-01902-z.
- [33] Z. Y. Cheng, Z. G. Zhang and Q. Nie, "Numerical simulation study on the degree of submarine cable protection by riprap protection layer against anchor," *Earth Environ*, vol.300, no.2, Aug. 2019, DOI: 10.1088/1755-1315/300/2/022127.
- [34] C. J. Fu, J. G. Wang, T. L. Zhao and Y. Lv, "Experimental study on the influence factors of flow velocity structure and turbulent characteristics in open channel with biomimetic grass," *Advances in Civil Engineering*, vol. 2021, Sept. 2021, DOI: 10.1155/2021/5512536
- [35] DNV. DNV - RP - F107. Risk assessment of pipeline protection, 2010.



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