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Posted Date: 2 March 2026

doi: 10.20944/preprints202603.0051.v1

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Article

An Empirical Examination of the Adverse and Favorable Effects of Marine Environmental Conditions on the Durability of Optical-Fiber Submarine Cables

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Abstract

This study investigates the factors contributing to the degradation of spirally wound armored steel wires used to protect core-structured unarmored optical-fiber submarine cables, driven by coupled multi-factor corrosion mechanisms in marine environments. It also assesses the influence of physical properties of deep-sea sediments on the durability of unarmored cables. The objective is to establish a scientific basis for cable longevity by integrating theoretical insights with empirical evidence. Although the steel utilized in armor is cost-effective and durable, it remains vulnerable to corrosion. Since the inaugural practical deployment of submarine communication cables between the United Kingdom and France in the 1850s, only a limited number of studies worldwide have examined the armor's corrosion and durability. Furthermore, there is limited literature on the physical characteristics of deep-sea surface sediments that directly affect the service life of the mechanically fragile polyethylene sheath. An in-depth analysis of cable damage and environmental conditions observed during maintenance operations offers valuable insights into the primary environmental factors influencing armor corrosion behavior and cable longevity. This research aims to provide essential guidelines for future cable system design and to support the development of effective strategies to enhance the sustainability and durability of cable systems operating in marine environments.

Keywords: armor corrosion; optical-fiber submarine cables; multi-factor coupling corrosion; ocean basin sediment; Tsugaru Strait

1. Introduction

Since the introduction of submarine communication cables in the 1850s, they have been mechanically protected against human threats by wrapping steel wire in a spiral around the core. Armoring techniques are still used in contemporary, mainstream optical-fiber submarine (hereinafter, OFS) cables. The reason is that steel wires are highly economical and durable. One of the noteworthy features of state-of-the-art cable technology, implemented in practice in the 1980s, is its ability to transmit substantial amounts of data at high speeds and at low cost. With the advent of digital society, remarkable advances have been made in meeting this demand. Figure 1 shows the use of each regional international bandwidth. As global internet data consumption continues to escalate exponentially, international bandwidth is expected to reach approximately 1280 Tbit/s by 2022 [1]. OFS cable systems are the vital infrastructure of international undersea communication, delivering essential information that sustains and enriches our social lives.

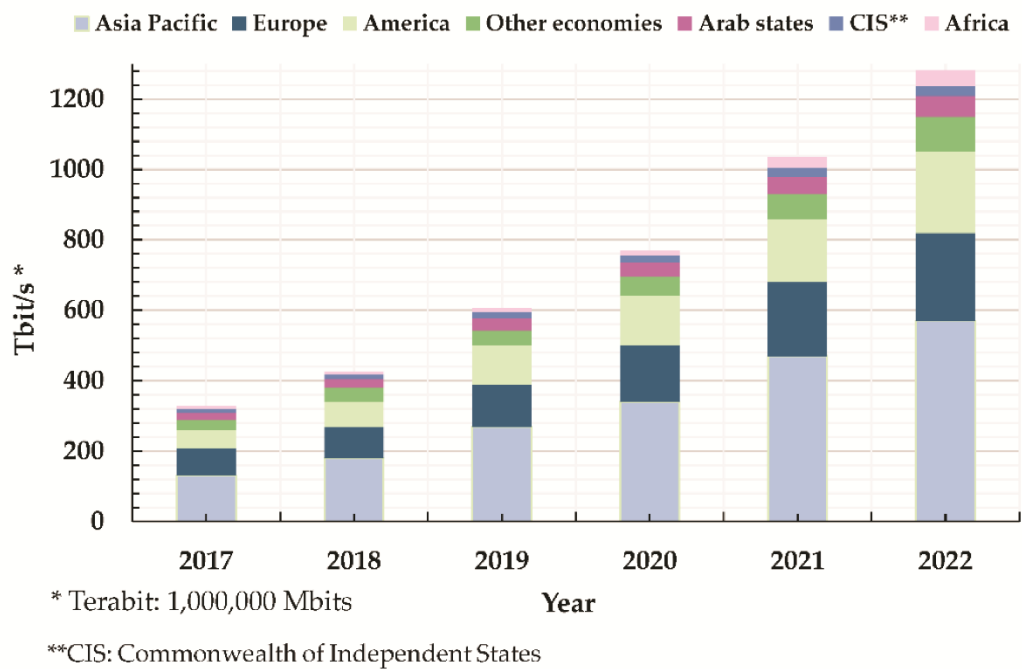


Figure 1. International bandwidth usage by region.

Despite major advancements in optical transmission technology, the cable’s mechanical structure has changed little since the 1980s. Section Two details this structure. Once the OFS cable is installed, it is technically impossible to remotely monitor the mechanical integrity of the entire armored steel wire (hereinafter, armor) at the landing stations. As a result, only corrective, not preventive, maintenance is possible, creating a major reliability challenge. Cable failures then require intervention from repair ships, resulting in system outages and substantial economic losses. Therefore, reducing failures caused by environmental factors is critical, and relying on empirical guidelines based on historical data helps build more dependable systems. The durability of armor against corrosion has been extensively investigated, particularly in submarine power cables for offshore energy development [2]. To date, no publications have addressed armor corrosion in OFS cables in marine environments.

This study aims to identify the positive and negative factors affecting the designed lifetime of OFS cables, which are essential to global socio-economic activities, and to improve their durability, cost-effectiveness, and maintainability through an evidence-based approach. To achieve this objective, empirical evidence from cable maintenance operations is used to analyze environmental factors that affect cable failures and service life. Also, it refers to the findings of the following previous studies:

To understand the essence of this research, it is essential to integrate knowledge from diverse disciplines. Previous studies across various fields provided objective evidence supporting this study. Reference [3] examines the erosion-corrosion phenomenon affecting materials used in industrial equipment and reveals that when static materials interact with dynamic liquids, the potential for corrosion thinning of armor due to erosion and corrosion increases significantly. The literature [4] on Corrosion Engineering considers various environmental factors that affect the corrosion of steel under marine immersion conditions. Experiments have clarified the effect of seawater flow velocity on steel corrosion. References [5,6] discuss the corrosion of armor in a marine environment, as observed in domestic coaxial submarine cables installed in Japan in the 1950s. Three factors have been identified as causes of armor corrosion: electrochemical corrosion, mechanical wear, and local battery effects. Theoretical analysis and field experiments have proved that electrochemical corrosion induced by the Earth’s magnetic field through seawater motion is the primary factor. Literature [7]

on civil engineering analyzed ocean currents in the Tsugaru Strait in northern Japan to investigate the potential for harnessing natural energy resources for ocean current power generation. This strait has a canyon-like terrain where ocean currents and tides collide, creating specific areas of complex, swift seawater flow, as detailed further in Section 3. The study provides evidence, through simulations, of ocean current behavior in specific regions. The literature [8] on seafloor soil engineering discusses the geotechnical characteristics of surface sediments derived from the deep ocean floor, particularly in areas with manganese nodules in the Central and East Pacific basins.

This article is organized into six sections to ensure a thorough and impartial review. Section 1 gives background, reviews prior studies, and outlines relevant issues to establish the context for this research's aims and significance. Section 2 analyzes OFS cable structures, examines their behavior on the seabed, and identifies common failures caused by environmental factors. Section 3 focuses on the geology of the Tsugaru Strait and analyzes cable failures in armored cables. Section 4 highlights the properties of deep-seafloor sediment and explains how they relate to the extended lifespan of unarmored cables. Section 5 examines the chemical makeup of seawater and the conditions that lead to armor corrosion, and provides examples of erosion and corrosion, along with an assessment of armor's expected service life. Section 6 summarizes the study's principal conclusions, based on a comprehensive analysis and rigorous methods.

2. Overview of Mechanical Cable Design, Physical Characteristics, and Typical Cable Failures Caused by the Marine Environment

This section provides a detailed technical overview of OFS cable structures and their post-installation behavior on the seabed. It specifically focuses on the mechanisms of cable insulation failures, illustrating the characteristics and mechanical vulnerability of the polyethylene (PE) sheath.

2.1. Mechanical OFS Cable Structures

Figure 2 shows an OFS cable cross-section, indicating its maximum design water depth and marine ecological water depth categories [9,10]. The cable's mechanical structure is modeled after coaxial submarine cables, which became mainstream in the 1950s. In the 1980s, the development of practical OFS cables led to the introduction of various new types, all using lightweight (LW) unarmored cables as their core. Currently, cable types are classified by their structural characteristics as either armored or unarmored.

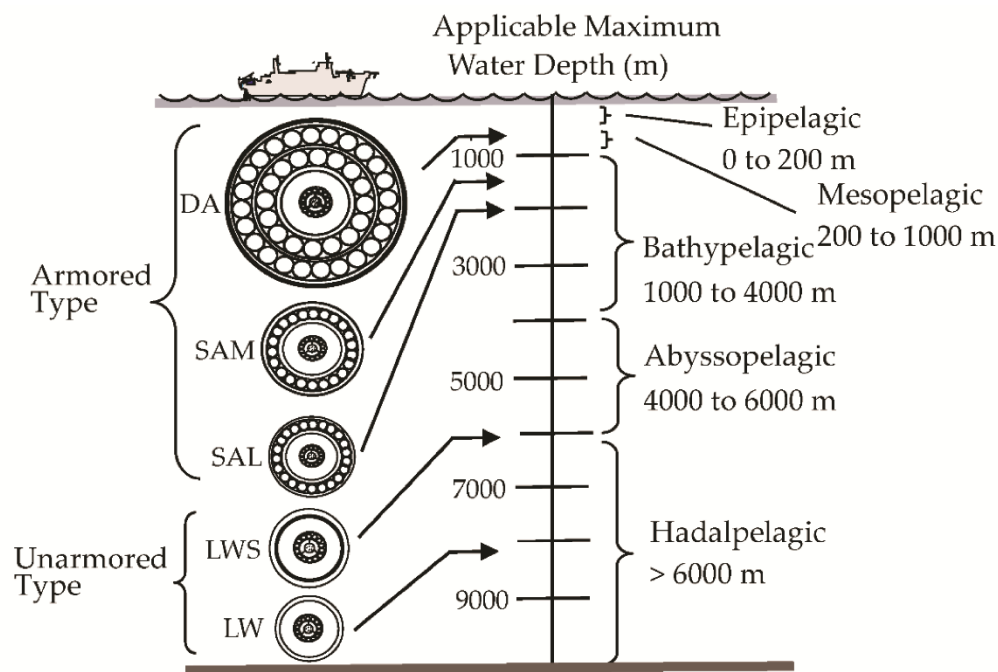


Figure 2. Cross-sectional illustration of cable types and their corresponding applicable maximum water depths.

2.1.1.1. The Application Ratio of Cable Types on a Global Scale

Figure 3 illustrates the distribution of the ratio across various water-depth ranges beneath the Earth’s surface [11]. The bathypelagic and abyssopelagic zones, which range from 3000 to 6000 meters in depth, constitute approximately 53.5% of the total ocean. In these regions, unarmored LWS types are often employed. In long-distance transoceanic systems, repeaters are spaced at 60 km intervals to amplify attenuated optical signals. The optical amplifiers in these repeaters use DC power, delivered from the shore with a constant current of 1 to 1.5 A through the cable’s copper tube (see Figure 4). The power-feeding system uses the Earth return system. Hence, the PE layer is critical for maintaining insulation; however, it is mechanically vulnerable to frictional damage from cable-handling equipment, the ship’s hull, and the seabed. If the power-feeding conductor contacts seawater due to damage to the PE layer, the insulation may fail. Analyzing the mechanical degradation of the armor and damage to the PE layer helps improve the system’s mechanical stability in dynamic, long-term marine environments. Details regarding this matter are outlined in Sections 3 and 5.

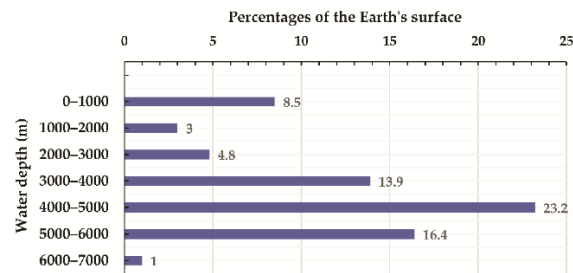


Figure 3. Percentage distribution of water depth across various ranges beneath the Earth's surface.

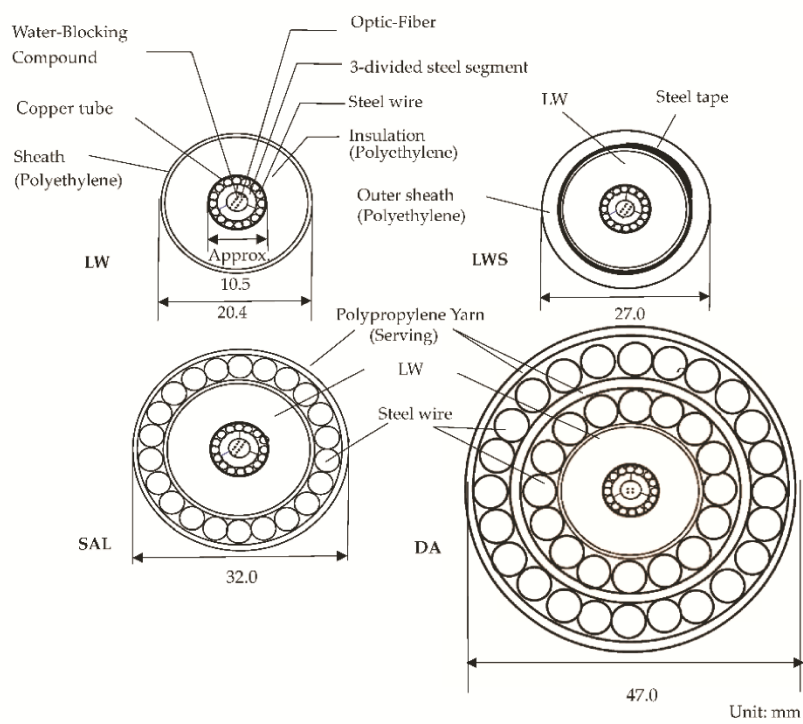


Figure 4. Overview of the cross-sectional construction of each cable type, illustrating the mechanical protection of the LW core.

2.1.2. Armor Philosophy

The design of cable armoring must ensure adequate mechanical protection for the cable core from external forces, such as fishing gear and anchors, during installation and operation. Literature [12] presents a philosophy for core protection: shallow-water cables use heavy armor, while deeper cables use lighter armor to reduce stress on the optical fiber. This allows deployment to a maximum depth of 1500 m for deep-sea fishing.

Although this approach provides sufficient mechanical protection for the cable, it does not mitigate corrosion, which may reduce the armor’s longevity in marine environments. Sections 3 and 5 investigate corrosion factors in needle-tipped armor and utilize objective evidence collected during maintenance and physical evidence from other cases to assess the service life of the wire.

Table 1 provides the physical specifications of cables commercialized in Japan during the early 2000s, facilitating a comprehensive understanding [10]. Figure 4 illustrates the cross-sectional construction of each cable type [10,13], which provides mechanical protection for the LW core, as detailed in Table 1.

Table 1. Mechanical Characteristics of OCC-SC300 cable series.

Cable type	Outer Diameter (mm)	Weight in air (kN/km)	Weight in water (kN/km)	Braking load (kN)	Applicable water depth (m)
DA: Double Armored	47.0	64.2	50.0	800	≤ 500
SAM: Single Armored Medium	34.0	30.6	22.9	380	≤ 1500
SAL: Single Armored Light	32.0	23.5	16.8	310	≤ 2000
LWS: Light Weight Screened	27.0	11.0	5.4	98	≤ 6000
LW: Light Weight	20.4	7.9	4.7	98	≤ 8000

2.1.3. Details of Mechanical Protection for the Cable Core (LW)

Table 2 presents the differences in mechanical protection methods and handling characteristics for unarmored cable LWS, armored cable SAL, and DA, with the basic construction LW as the core. The LWS is wrapped with a thin steel tape that surrounds the LW. This protects it against potential damage from severe friction with the ship’s hull or seabed, or from shark bites. Conversely, the armored cable incorporates a steel wire encircling the LW to provide mechanical protection. To prevent corrosion in marine environments, the armor surface is galvanized. It is then spirally wrapped with a layer of bitumen-impregnated polypropylene yarn (Serving layer). Nonetheless, the serving layers are considered sacrificial; any minor damage sustained during loading onto the cable ship, handling, or installation is deemed insignificant. Additionally, this layer significantly restricts water exchange within the enclosed spaces beneath it. This reduces corrosion rates [14].

Table 2. Protection Method of Cable Core.

Cable Type	Protection Method of Core LW	Protection Method of Armor	Amount of cable twist due to the dynamic change in cable load
LWS	It is wrapped in thin steel tape.	Not applicable	The LWS has the protection structure described in the left column, minimizes twisting during dynamic changes in cable loads by laying, offers excellent operability, and has a proven history of usability beyond the design depth.
SAL	φ3.2×22 Galvanized steel wires.	Polypropylene yarn with bitumen impregnation.	Compared with DA, twisting is less pronounced, but careful management remains essential.
DA	φ4.6×16 (inner) φ4.6×24 (outer). Galvanized steel wires.	Polypropylene yarn (inner, outer) with bitumen impregnation.	During installation and repair operations, particularly during dynamic changes in cable loads, significant twisting occurs, posing a substantial risk of optical fiber damage due to cable kinking.

2.2. Behavior of Cables on the Seabed

Figure 5 illustrates the installation across three conditions (areas A–C) using the surface-laying method, which involves carefully deploying cables and subsea plants directly onto the seabed. Each area presents unique topographical characteristics and sedimentary compositions of the seabed surface. Figure 6 shows the behavior of the cable after laying for each of the bottom features under

both soft and hard seabed surface conditions. Table 3 describes the cable’s behavior on the seabed for each area.

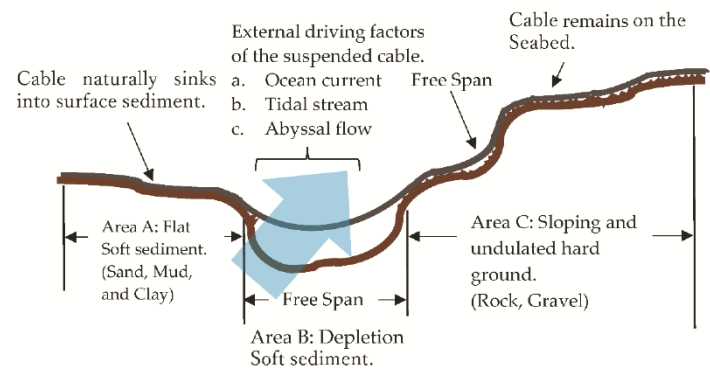


Figure 5. Examples of cable installations utilizing the surface-laying method across diverse undersea topographies.

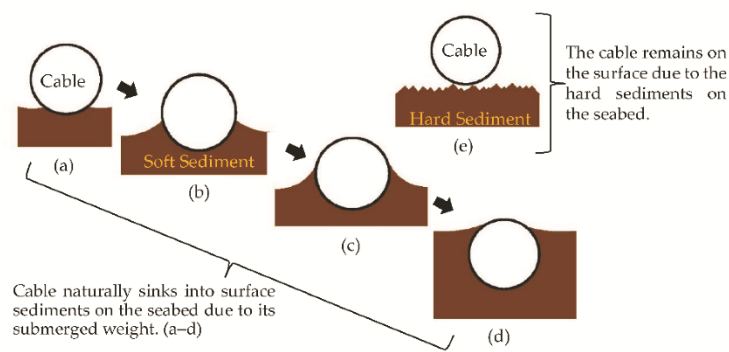


Figure 6. The behavior of cables on the seabed under both soft and hard seabed surface conditions.

Table 3. Cable Behavior Under Different Seabed Conditions. (see Figures 5 and 6)

Area	Topography and surface sediment	Description
A	Flat, soft ooze	Over time, the cable's submerged weight causes it to naturally sink into the sediment. As a result, isolated from external forces such as ocean currents, tides, and abyssal currents, they remain stable due to static frictional forces exerted by the surrounding deposits.
B	Depression, soft ooze	Because of the cable's bending stiffness, the Free Span (FS) section cannot conform to the depression, resulting in a suspended cable. When the seawater flows pass through the FS, there is a risk of abrasion damage to the cable, especially at the support points at both ends.
C	Slope, Rocky	Because the seabed has a hard surface, the cable stays in position on the seabed, and currents can easily shift the cables due to the lower friction from sediment in the seabed. Small-scale FS occurs.

2.3. Examples of Damage to the PE Insulation Layer

Figure 7 illustrates a typical insulation failure that occurs when the PE insulator in armored cables is damaged due to environmental factors, and Figure 8 shows the same failure in unarmored cables. Mechanical damage from external forces, such as friction, is clearly the main cause of

insulation failure in both cable types, rather than electrical degradation of the PE insulation caused by the DC feeding power used to drive the repeaters. Table 4 details each failure condition.

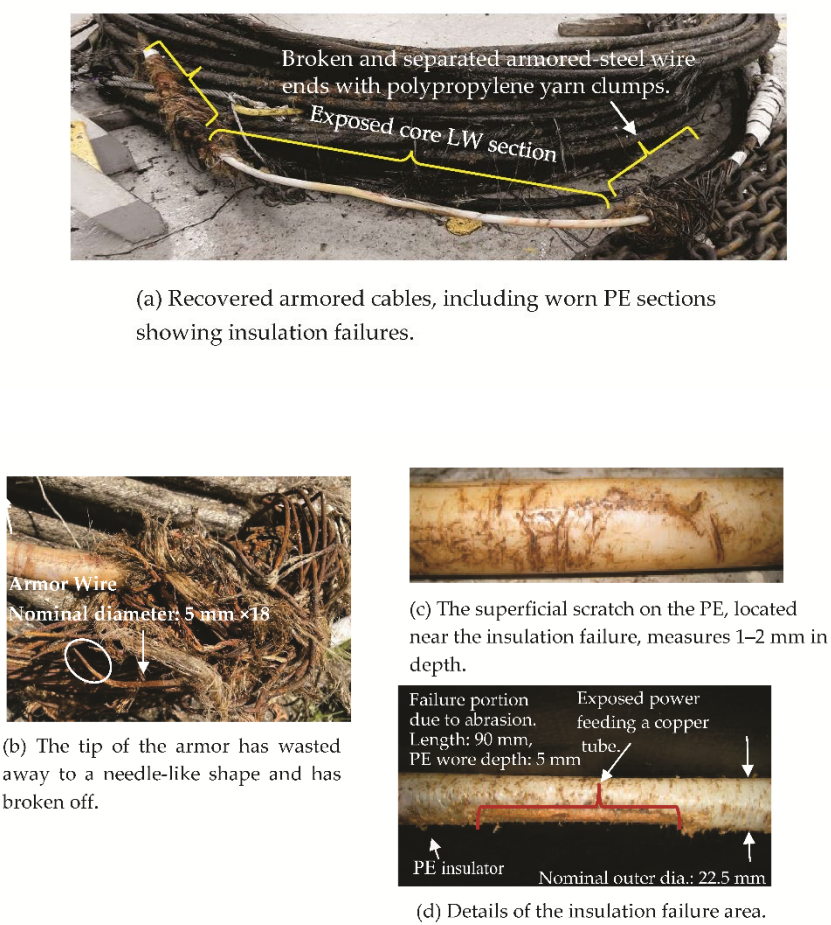


Figure 7. (a–d) A detailed view of an insulation failure within a section of the single armored cables.

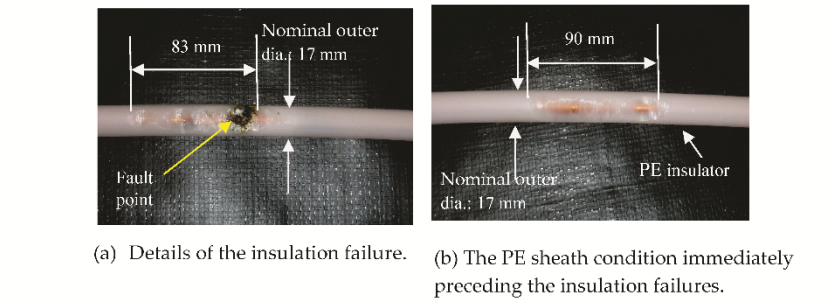


Figure 8. (a, b) A detailed view of an insulation failure within a segment of the unarmored cables (LW).

Table 4. Details Concerning Damage to the PE Insulation Layer.

Ref. Figure	Cable Type	Water Depth (m)	Laying method	Changes in cable condition affect insulation failure	Identification of failure locations and the undersea environment
7	Single armored (SAM)	200	Surface Lay (The application of the burial method was not possible due to the underlying feature forming a steep slope of rock.)	(1) The tip of the damaged armor is needle-like due to corrosion wastage (shown by the white circle in Fig. 7(b)). When a cable is subjected to external forces and vibrates, the spirally wound armor wire gradually fails due to metal fatigue.	Tsugaru Strait. Within narrow straits, cauldrons sculpt the seabed, setting up steep valleys. The Tsugaru Warm Current, which flows eastward through this topography, interacts with tidal streams that periodically vary in response to tidal-level fluctuations on both sides of the strait, producing intricate, rapidly flowing currents. Details will be described in Section 3.
				(2) Residual forces within the armor shrink both ends of the broken armor axially along the cable, simultaneously pulling on the polypropylene threads that protect the armor from corrosion. As a result, the core's LW is exposed. (Fig. 7(a))	
				(3) Furthermore, numerous surface scratches and complex friction marks were observed on the LW surface (Fig. 7(c)), indicating exposure to a harsh environment.	
				(4) At the fault location shown in Fig. 7(d), a part of the PE has worn away in the cable's axial direction, exposing the power-feeding conductor.	
8	Un-armored (LW)	4000–6000	Surface Lay	The contact surface between the cable and the seabed in a hanging section has sharp edges which cause localized damage to the PE sheath due to friction, exposing part of the power-feeding conductor.	A decreasing thickness of surface sediments has been reported in the subduction zone of the Northwest Pacific; see Section 4 for details.

3. Examination of the degradation of Armor

This section analyzes the correlation between topography and seawater flow, considering environmental factors related to the damage, as the damaged segments of the armored cable were predominantly located in regions with swift seawater flows.

3.1. A Geographical Overview of the Studied Area

Figure 9 depicts the characteristic ocean current system encircling the Japanese archipelago. The Tsushima Current flows north through the Japan Sea, splitting into the Soya Warm Current (SWC) via the Soya Strait and the Tsugaru Warm Current (TWC) via the Tsugaru Strait. This process connects the Japan Sea and the North Pacific Ocean. The Studied Area focuses specifically on the Tsugaru Strait (hereinafter, strait).

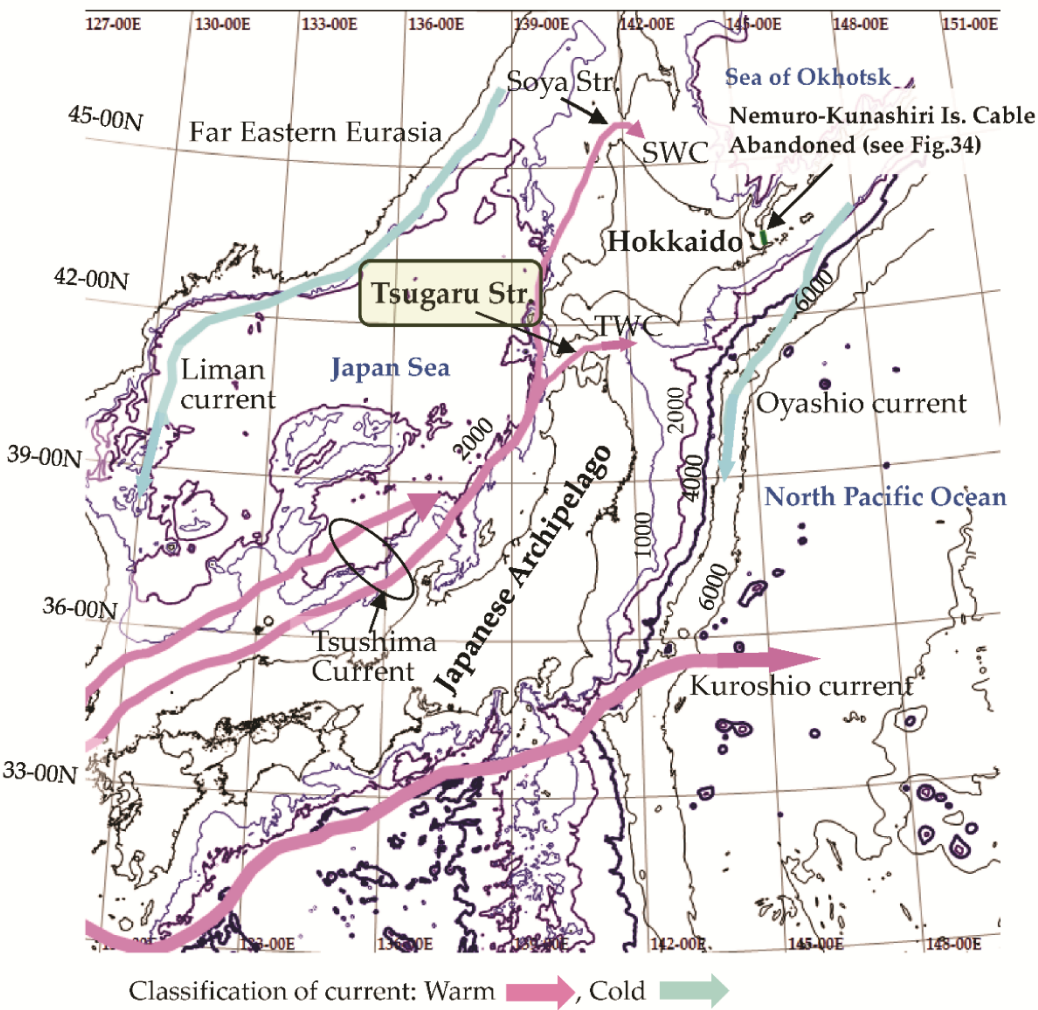


Figure 9. The ocean current system surrounding the Japanese archipelago.

3.1.1. Location of the Cable System Under Study

Figure 10 shows a map of the strait between Hokkaido and Honshu. The Strait is an important sea route and a major fishing area for small boats. The TWC, a branch of the Tsushima Current, flows eastward through the strait. It transports heat, salt, marine life, and larvae from the Japan Sea into the North Pacific, thereby further affecting the Strait’s ecosystem. Furthermore, tidal currents resulting from the difference in tidal levels between the eastern and western coasts of the strait are superimposed upon the TWC, and thereby the seawater flow periodically becomes more complex. The underwater communication cable system studied runs east-west across the Strait and is partly buried by plowing, while submarine power cables and railway tunnel infrastructure cross it north-south. For economic security reasons, the exact cable routes are not disclosed; only the location of the cable failure under study is displayed. The legend for Figure 10 is provided in Table 5 [15]. Table 6 presents details of the electrical submarine power cable system [16].

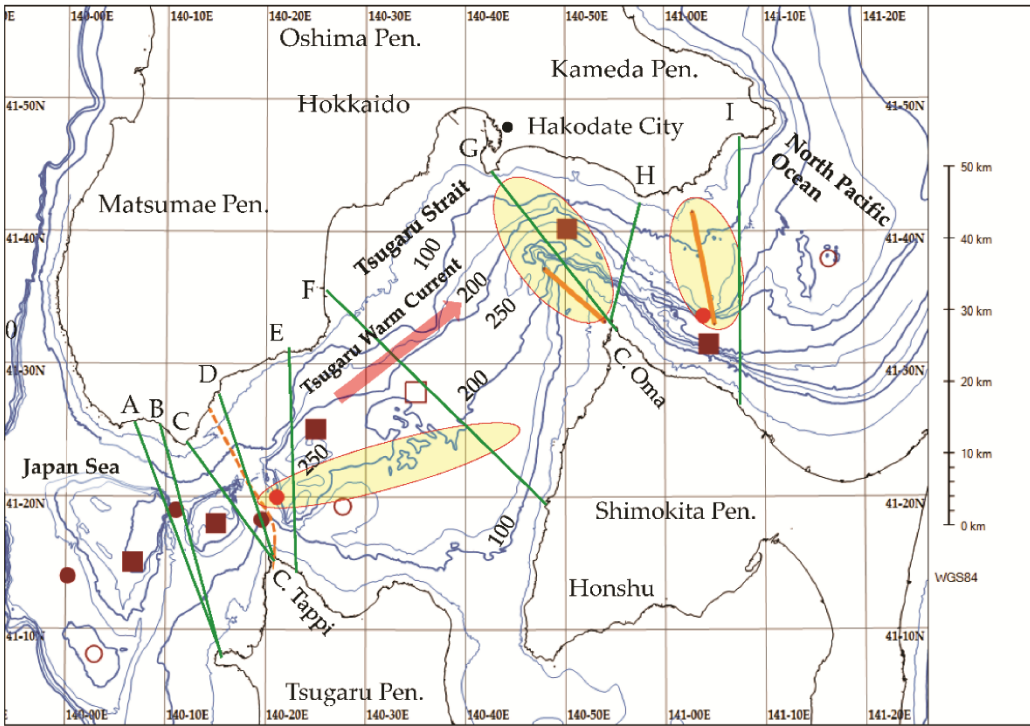


Figure 10. A comprehensive depiction of the Tsugaru Straits and its adjacent coastal region. Isobaths are shown as solid purple lines at 50-meter intervals, derived from digital bathymetry data (M7000 series) from the Hydrographic and Oceanographic Department of the Japan Coast Guard.

Table 5. Legend of Figure 10.

Symbol Line and Mark Type	Name	Remarks
Bright orange dashed line: ---	Seikan-tunnel	Beneath the seabed, the 100-meter designated railway runs on a 25 kV AC, 50 Hz electrical system.
Bright yellow-filled and delicate red oval	Region of swift flow	The geographical regions of Western, Central, and Eastern.
Red-filled circle: ●	Cable FP (Failure Point)	The geographical location of Western and Eastern.
Rectangle filled with brown: ■	Caldron	Matsumae, Tayama, Suda, Oma, and Shiokubi (From the West)
Brown-filled circle: ●	Saddle	Shirakami and Tappi (From the West)
Brown rectangle: □	Basin	Tsugaru
Brown circle: ○	Bank	Nishi Tsugaru and Tappi (From the West)
Orange bold line: —	Spur	Oma and Shiokubi (From the West)
Green solid line: — (A-I)	Not applicable	Survey line for the cross-section of topography.

Table 6. The details of the submarine power cable system.

Items	Details
Operational Voltage, Capacity	250 kV DC, 600 MW
Circuit Type	Bipolar with a Dedicated Metallic Return Path for Monopolar Operation
Cable Protection	Buried or artificial pipes are installed at depths of up to 60 meters below the water surface.

The total cable length of the studied communication cable system is approximately 100 km, as shown in the cross-sectional view of the seafloor along the designated cable route in Figure 11, which clearly indicates the relative positions of each infrastructure intersection. The proportions of construction methods in the study area are shown in Figure 12.

The east-west cable failure points were located within the Surface Lay area, where the cable is laid directly on the seabed. This occurred due to the steep slope and rocky seabed. On flat terrain, the cable-burying method achieved a burial rate of 52%. The failure locations coincide with regions of swift seawater flow, strongly influenced by seabed topography (see Figure 13; the nearest survey lines are E and I). Thus, rapid ocean currents and tidal streams are significant contributors to cable failure. Further analysis of these factors is presented in Section 5.

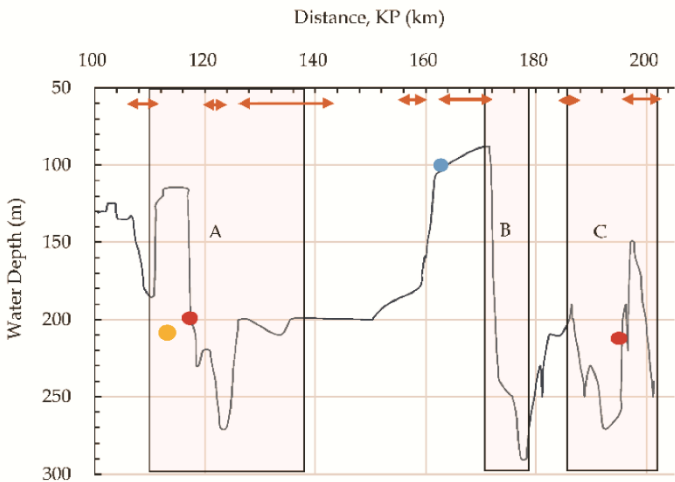


Figure 11. A cross-sectional depiction of the seabed along the planned route of the studied communication cable system. The regions shaded in light red (A, B, and C) signify areas of increased flow velocity. The red-filled circle designates the site of cable failure, while the orange-filled circle denotes the railway tunnel, as illustrated in Figure 10. Furthermore, the light-blue-filled circles indicate the locations where the submarine power cables intersect. The light-brown arrow points to the designated cable-burial area.

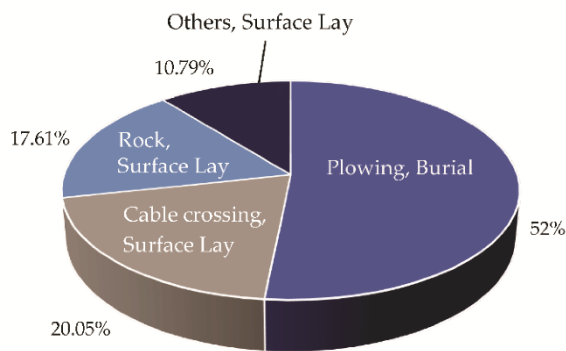
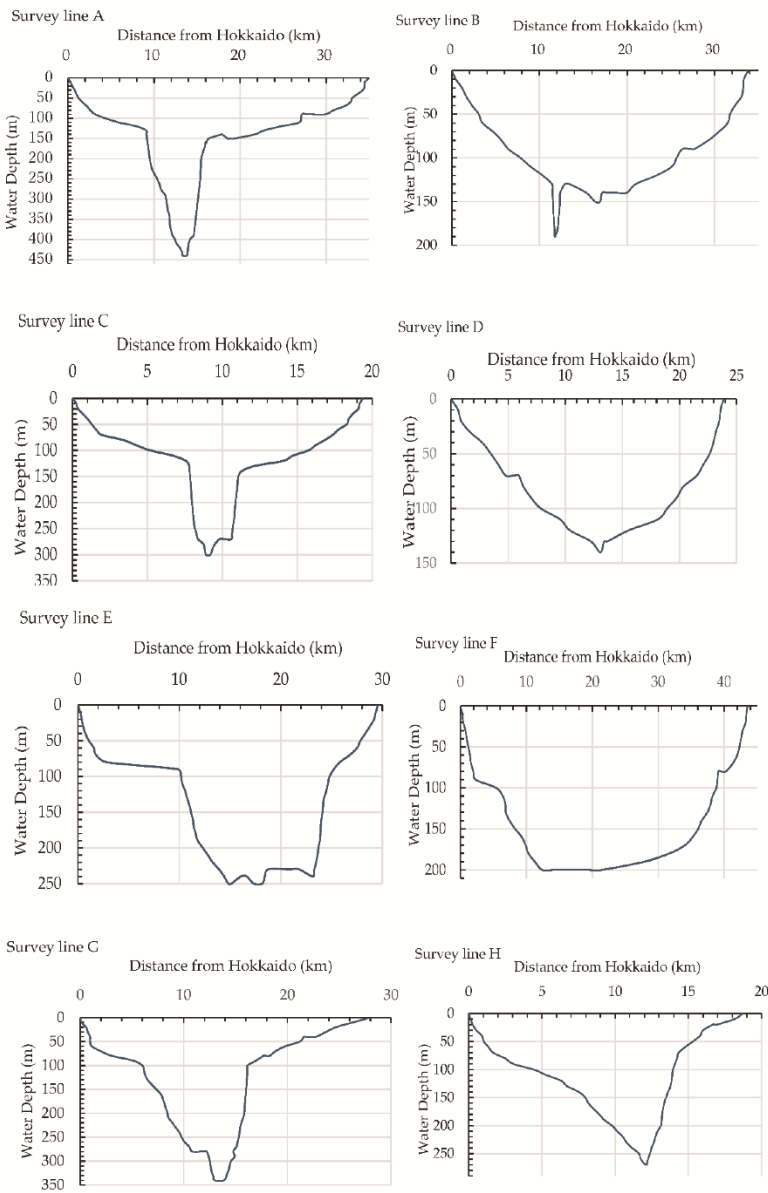


Figure 12. Proportion of Construction Methods employed in the studied system.



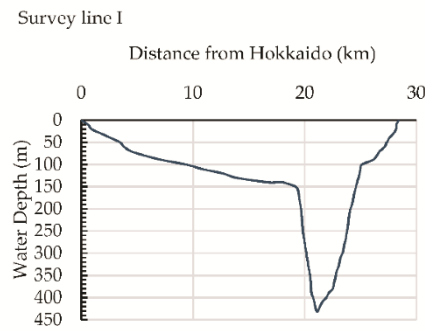


Figure 13. The topographic profile along survey lines A–I.

3.1.2. Characteristics of the Tsugaru Strait

The seabed topography in this strait is complex, with five caldrons running west to east and spurs running north to south at depths of 280 to 350 meters. This geomorphic layout, together with tidal streams, ocean currents, and the V-shaped valley produces swift seawater flow in some areas (see Figure 10). Simulations indicate that velocities at the western entrance may reach 1.8 m/s [7]. Literature [17] reports rocks along the caldron’s edges and sand dominating the surrounding seabed. Figure 13 presents a comprehensive cross-section of Strait’s topography. This illustration corresponds to the green solid lines A–I shown in Figure 10. The middle area, designated survey line F, shows a flat profile. In contrast, the other lines show concave or V-shaped profiles, particularly the steeply V-shaped lines A, C, G, H, and I, which are attributed to geological activity.

3.1.3. Geological Comparison of the Tsugaru Strait and the Soya Strait

We will compare the Soya Strait and Tsugaru Strait, the principal conduits of the Tsushima Current into the North Pacific Ocean, to examine differences in hydrographic and hydrodynamic conditions, including ocean current velocities, that significantly contribute to armor degradation.

Figure 14 shows the widths at different depths at the narrowest section, enabling comparison of the Tsugaru and Soya Strait channel configurations that carry the Tsushima Current branch. The Soya Strait is about 42 kilometers wide and up to 70 meters deep, featuring a gently sloping seabed and a broad channel. In contrast, the Tsugaru Strait has a V-shaped profile, is approximately 19 kilometers wide, and reaches a maximum depth of about 310 meters, thereby enhancing seawater flow velocity in that area.

There are notable distinctions in the topographical profiles of the two straits, indicating that swift seawater flows characterize the Tsugaru Strait. This factor significantly contributes to armor corrosion and is a key finding in our study.

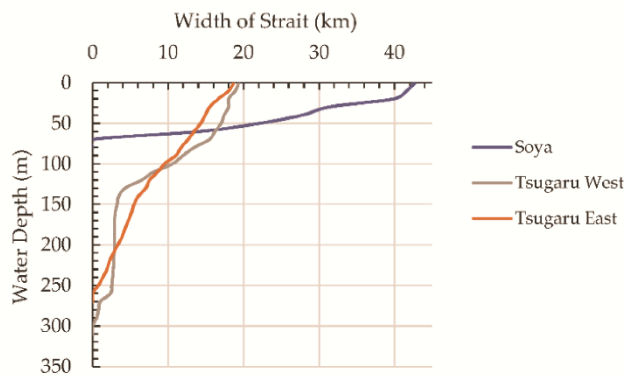


Figure 14. The correlation between the depth and width of the Tsugaru Strait and the Soya Strait, particularly at their narrowest points.

Table 7 presents a comparative analysis of the geographical features of the two straits.

Table 7. Geological Comparison of the Tsugaru Strait and the Soya Strait.

Strait/Comparison Items	Narrowest Width Points (km) See Figure 14	Terrain Profile See Figures 13 & 14	Water Depth (m) See Figure 14	Geology on the Seabed [17]	Variation in West-East Sea Level (cm)	Mean Volume Transport (Sv*)	Maximum Flow Velocity (cm/s)	Vertical Component of the Earth's magnetic Field in 2020 (nT) [20]
Tsugaru	19.4 (West) 18.7 (East)	V-Shaped Canyon	310 (West) 260 (East)	Rock, Gravel, Sand	10–27 [18]	1.0–2.3 [18]	150 [18]	41,000
Soya	42.7	Gentle	70	Rock, Gravel, Sand	10 [19]	1.0–2.0 [19]	60 [19]	46,000
Comparison Result	Approx. double Soya>Tsugaru	Tsugaru: Steep slope Soya: Gentle	Approx. 3.7 to 4.4 times Tsugaru>Soya	Almost the same	Approx. 1.0–2.7 times Tsugaru>Soya	Approx. 1.0–1.15 times Tsugaru>Soya	Approx. 2.5 times Tsugaru>Soya	Almost equal

* Sv (Sverdrup) equal to 10⁶ m³/s

3.2. Comparison of Cable Failures See Figures 10 and 11

Table 8 compares cable failures observed on the eastern and western sides of the Strait.

Table 8. Comparison of cable failure conditions.

Failure location and comparative items	West	East
System completion year	1999	Identical to the left
The time of failure and the number of years since completion.	2010: 11 years later	2021: 22 years later
Cable type	Single armored type (SAM)	Identical to the left
Location	KP117	KP195
Region of swift flow.	KP111–137, Zone A	KP187–201, Zone C
Water depth (m)	205	219
Geographical features:	Caldron	Spur
Terrain gradient (degrees)	>20	Identical to the left
Bottom feature	Rock	Identical to the left
Failure category	Insulation failure	Identical to the left
Laying method	Surface Lay	Identical to the left
Failure cause	See Table 4, SAM	Identical to the left
Distance and direction from artificial structures that intersect the system under investigation.	2 km northeast of the railway tunnel.	24 km northeast of the power cable.

3.3. Consideration of Cable Failure

Based on the analysis above, the environmental factors that are detailed in Section 5 are responsible for cable failures in both the eastern and western regions. Armor corrosion results from these multi-coupled environmental factors. Although an AC-electrified railway tunnel and submarine power cable are near the fault area and cross the studied communications system, there is no clear evidence of armor corrosion from stray currents originating from these artificial sources. Furthermore, no other industrial activities, such as fishing, contributed to the cable failure (see Figure 7 (a–c)), and human factors were not responsible.

4. The Relationship Between Physical Characteristics of Deep-Sea Sediments and the Durability of Unarmored Cables

This section reviews the physical properties of deep-sea surface sediments, focusing on evidence from prior studies and cable maintenance activities in the Northwest and Central Pacific.

4.1. Statistics of LW Cable Failures in the Deep-Sea Region

The global rate of cable failures at depths greater than 1000 meters remains low, with a 10% rate reported in 2024 [21]. These statistical findings strongly indicate that PE sheathing may be protected by seafloor sediments when using unarmored cables in this depth range.

To verify this trend, we analyzed cable maintenance records from 1999 to 2016 for water depths over 500 meters in the northwest North Pacific Ocean [22]. This area has complex interactions among the Eurasian, Pacific, North American, and Philippine Sea Plates, which have been active since Earth’s formation. Tectonic activity has led to trenches, troughs, and chains of seamounts along these plate boundaries. Cables, especially unarmored ones in deep-sea environments, face hazards from natural events and steep terrain. Our analysis shows that LW cable failures mainly occur on steep slopes. Figures 15–18 show statistics on LW cable failures.

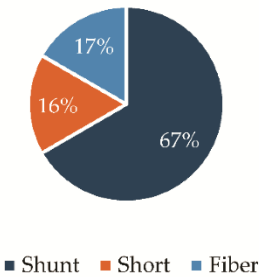


Figure 15. Proportion of Fault Category.

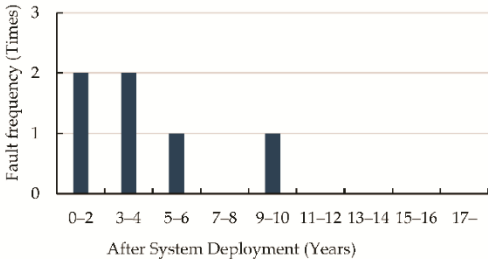


Figure 16. Number of faults versus after system deployment.

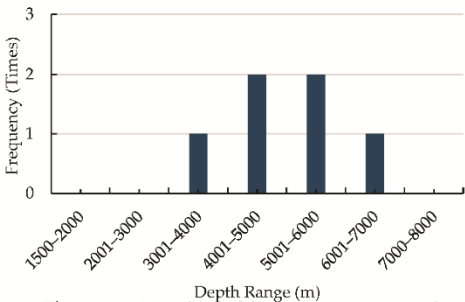


Figure 17. Number of faults versus water depth.

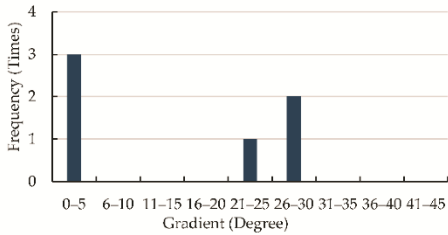


Figure 18. Number of faults versus the gradient of the seabed.

4.2. Results of Failure Analysis

Shunt failure, synonymous with insulation failure, is the primary cause, accounting for 67% of cases that occur between 2 and 10 years after system deployment. These incidents occur at depths ranging from 3001 to 7000 meters, within seabed slope gradients of 0°–5° and 21°–30°. The failure observed in the flat region between 0° and 5° is attributed to the behavior of the underwater cable during repeater deployment [23].

4.3. Distribution of Principal Sediment Types in the North Pacific Ocean

Reference [24] reported a comprehensive lithological classification of oceanic sediments in 2015. Clayey and calcareous deposits predominate in the sediments, and details for the North Pacific region are presented in Table 9. The primary sediments found on the seafloor of the North Pacific consist of 62% clay and 16% calcareous ooze.

Table 9. Distribution of the main sediment types in the North Pacific Ocean.

Ocean North Pacific	Clay (%)	Calcareous ooze (%)	Fine-grained calcareous sediment (%)	Radiolarian ooze (%)	Diatom ooze (%)	Mixed ooze (%)	Other (%)
120°E to 100°W, 59.5°N to 20°N and 120°E to 80°W, 20°N to 0°N	62	16	5	3	4	1	9

4.4. Mechanical Properties of Deep-Sea Sediments

To test the hypothesis that deep-sea sediments protect the unarmored cable sheath, we draw on previous studies of deep-sea sediments in the central and eastern Pacific basin and observational evidence from cable maintenance and the development of a cabled ocean-bottom seismometer system in the northwest Pacific. Figure 19 shows the locations of sediment samples collected or observed in the deep-sea Pacific Ocean; the legend is provided in Table 10.



Figure 19. Deep-sea Sediment Observation Site.

Table 10. Legends of Figure 19.

Mark type	Remarks	Reference
Rectangle filled with blue: ■	The vane shear strength of seabed surface sediment in the Central and East Pacific Basin.	[8]
Red rectangle: □	Location of recovered repeater.	[23]
Orange-filled circle: ●	A Remotely Operated Vehicle (ROV) measured the thickness of surface sediment on the seabed.	Section 4.5

4.4.1. Vane Share Strength (VSS)

To understand the engineering properties of deep-sea sediment, this study draws on prior research from depths of about 5000 meters in the East and Central Pacific Basin [8]. This location is approximately 2300 kilometers southeast and 4000 kilometers southwest of Hawaii. These regions are at depths exceeding the critical calcium carbonate compensation depth and are far from coastal areas. This depth significantly affects seafloor sediment composition, including fine particulates and siliceous biological remains.

Figure 20 shows only VSS, based on a diagram plotting VSS, sensitivity, cone-penetration resistance, and water content against depth below the seafloor. VSS is a key indicator of deep-sea sediment characteristics in geotechnical properties.

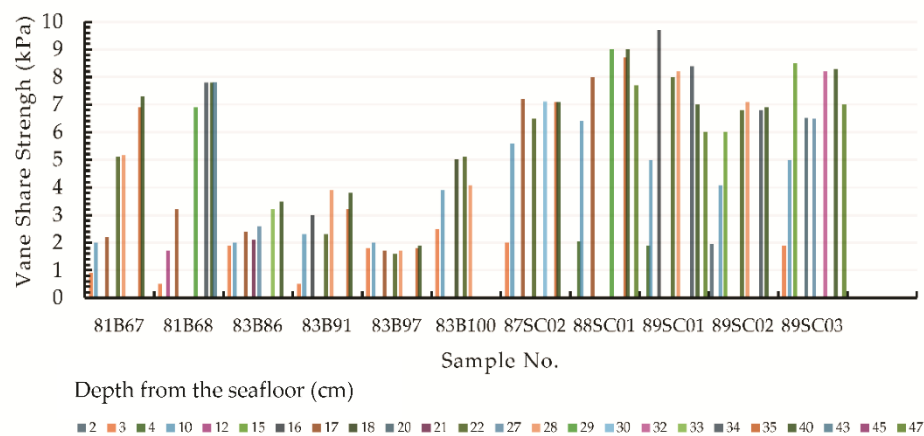


Figure 20. Result of on-board VSS measurement.

4.4.2. Consideration of VSS

Measured VSS is 2–9.5 kPa at depths of 20–40 cm from the seafloor. VSS peaks at 9.5 kPa at 34 cm in depth, showing clear softening from pelagic sediments. Sample No. 81 had a bottom slope of less than 5°, while the others were nearly flat. Even in flat marine settings, the deepest sample points vary. For samples No. 87–89, VSS steadily increased with more sediment depth.

4.4.3. VSS Evaluation

The clayey soils category for geotechnical engineering is based on mechanical (stress) properties, primarily unconfined compressive strength (UCS). Values of the UCS corresponding to the various degrees of consistency are given in Table 11 [25,26].

Table 11. The Consistency of Clay in Terms of UCS.

Consistency	UCS, Qu (kPa)
Hard	Over 400
Very stiff	200–400
Stiff	100–200
Medium, Firm	50–100
Soft	25–50
Very soft	Less than 25

The VSS (S) is computed using the conventional expression as equation (1) [27].

$$S = Q_u/2 \dots\dots\dots (1)$$

in which Qu is the UCS, defined as the maximum applied load divided by the average cross-section of the specimen. Equation (2) is derived from equation (1).

$$Q_u = 2 S \dots\dots\dots (2)$$

The measured S of the deep-sea sediments attains a maximum value of 9.5 kPa, and the Qu is ascertained to be 19 kPa utilizing equation (2). In comparison with Table 11, the deep-sea sediment consistency is categorized as “Very soft.”

Physical characteristics of Very soft: easily deformed when pressed firmly and exuded when squeezed.

4.5. An Observed Thickness of the Seafloor Surface Sediments

4.5.1. Subduction Zone

In recent years, the characteristics of ocean floor sediments at depths of 1000 meters or more have been observed visually using an ROV or crewed submersibles. Table 12 presents the results of sediment thickness measurements conducted on the seafloor using an ROV during an oceanographic survey. This survey aimed to install a submersible seismometer in the southeastern region of Hokkaido, Japan, within the southern Kurile subduction zone. Both locations were observed to contain unconsolidated soft sediments [28].

Table 12. Observed the thickness of surface sediments on the ocean floor.

Latitude (N)	Longitude (E)	Water Depth (m)	Thickness of surface sediment (cm)	Seabed slope* (Degree, a falling gradient)
41°52.914'	145°04.638'	3786	10	Approx. 1.5
41°39.909'	144°20.695'	2630	2–3	Approx. 5.4

*The seabed slope was calculated by analyzing the change in water depth and horizontal distance between each point using data from "Offshore Kushiro M7007 Ver.2.1" published by the Hydrographic and Oceanographic Department of the Japan Coast Guard in June 2012.

4.5.2. Oceanic Basin

Figure 21 shows the seismic sensor installed on the seabed in the Amami Trough at a water depth of 1100 meters, north of Okinawa, Japan. Figure 22 presents its mechanical outline [29]. This example shows the seabed sediment thickness at the sensor site, which roughly matches the sensor’s outer diameter of 216 mm. Furthermore, observations of patina erosion on the surfaces of most pressure vessels of repeaters recovered from the deep-sea floor during cable maintenance suggest that the thickness of the sediments in the oceanic basin is approximately 20 cm.[23] Conversely, physical evidence indicates that sediments in the Kuril subduction zone are only 2–10 cm thick.

Subduction zone sediments are comparatively thinner than those found in oceanic basins or flat seabed settings of the Trough.

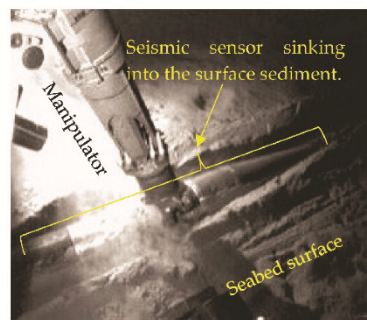


Figure 21. Observation of the installed seismic sensor on the seabed by an ROV.

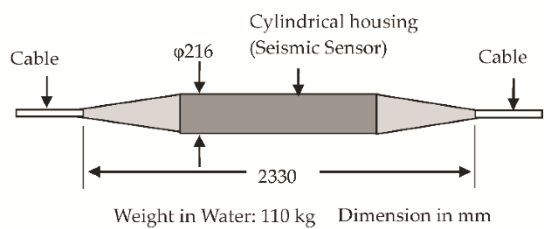


Figure 22. Dimension of seismic sensor.

4.6. Validation of Analysis Result

A geotechnical analysis of the sediments in the oceanic basin shows they predominantly consist of clay and calcareous ooze, with a UCS of up to 19 kPa and an estimated thickness of approximately 20 cm.

The concentration of unarmored cable failures along the subduction zone of the Japan Trench and Nankai Trough on the eastern side of the Japanese archipelago confirms a close relationship between sedimentary layer thickness and cable failure [22].

Long-term durability of unarmored cables in deep-sea environments, as evidenced by cable failure statistics and geotechnical analysis, supports the hypothesis that mud sediments act as a protective barrier against abrasion of the PE sheath, given their physical properties and thickness.

5. A Discussion of Multi-Factor Environmental Armor Corrosion and Durability

This section discusses the physical and chemical factors that influence armor corrosion in marine environments and assesses armor durability reviewing empirical evidence and proven records.

5.1. Definition of Corrosion

Corrosion, driven by coupled environmental factors, is a process in which materials undergo chemical and electrochemical reactions that cause wear, degradation, and destruction, resulting in the loss of their original functionality [30].

5.2. Fundamental Factors of Metal Corrosion in Marine Environments

The high concentration of free ions in seawater, coupled with elevated salinity and oxygen levels, renders it a highly corrosive environment. Corrosion-related degradation of the armor in the marine environment can be classified into four categories [31]. Table 13 shows major factors affecting armor corrosion in the marine environment. The analysis focuses on physical factors, including salinity, conductivity, and water velocity; chemical factors, such as elevated chloride ion concentration and dissolved oxygen levels; and metallurgical factors, such as the surface armor condition. Other items were excluded because no clear evidence was found.

Table 13. Major Factors Affecting Corrosion in the Marine Environment.

Physical	Chemical	Biological	Metallurgical
Temperature	High chloride ion concentration	Bacterial	Alloy composition
pH	Dissolved oxygen	Marine growths	Steel types
Salinity	High carbon content	Fouling	Surface conditions
Conductivity	Hydroxide ion	Pollutants	Surface roughness/ Surface finish
Seawater flow velocity	Carbon dioxide	Biomass	Protective coating

5.2.1. Composition of Seawater

The two most prevalent elements in seawater, after oxygen and hydrogen, are sodium and chloride [32]. Table 14 delineates the principal chemical constituents of dissolved electrolytes within seawater. Seawater contains a high concentration of Cl⁻ and Na⁺ ions, making it an effective electrolyte [33].

Table 14. Primary Ions Composition of Seawater.

Anion	g/kg seawater (35%)	g/kg/Cl%	Cation	g/kg seawater (35%)	g/kg/Cl%
Cl ⁻	19.354	0.9989	Na ⁺	10.77	0.5560
SO ₄ ²⁻	2.712	0.1400	Mg ²⁺	1.290	0.0665
Br ⁻	0.0673	0.00347	Ca ²⁺	0.4121	0.02127
BO ₃	0.0045	0.000232	K ⁺	0.399	0.0206
F ⁻	0.0013	0.000067	Sr ²⁺	0.0079	0.00041

5.2.2. Conductivity

Table 15 shows that the resistivity and conductivity of various water types, including seawater, are markedly higher than those of other water categories [34]. Consequently, dissolved salts reduce resistivity. Resistivity and conductivity are fundamental physical properties that characterize a material’s electrical conduction.

Table 15. Water resistivity and conductivity at 25 °C.

Type of water	Resistivity ρ	Conductivity σ
	[Ω -cm]	[μ S/cm]
Pure water	20,000,000	0.05
Distilled water	500,000	2
Rainwater	20,000	50
Tap water	1000–5000	200–1000
River water (typical)	2500	400
River water (brackish)	200	5000
Sea water (coastal)	30	33,000
Sea water (open sea)	20–25	40,000–50,000

5.2.3. Interaction Among Erosion, Corrosion, and the Fluid Environment

When armor is exposed to a corrosive environment, such as flowing seawater, chemical, mechanical, and electrochemical corrosion processes occur concurrently. Figure 23 depicts the interaction between mechanical erosion, chemical corrosion, and the fluid environment. This relationship indicates that erosive corrosion occurs only when erosion, corrosion, and the fluid environment are present concurrently [35]. It also shows that the interaction between seawater flow and the vertical component of Earth’s magnetic field induces an electromotive force in the armor, thereby increasing the corrosion potential and accelerating corrosion in areas where the armor’s corrosion-resistant surface layer is damaged. The equivalent circuit diagram of an armor under marine environmental conditions is described in Section 5.5.

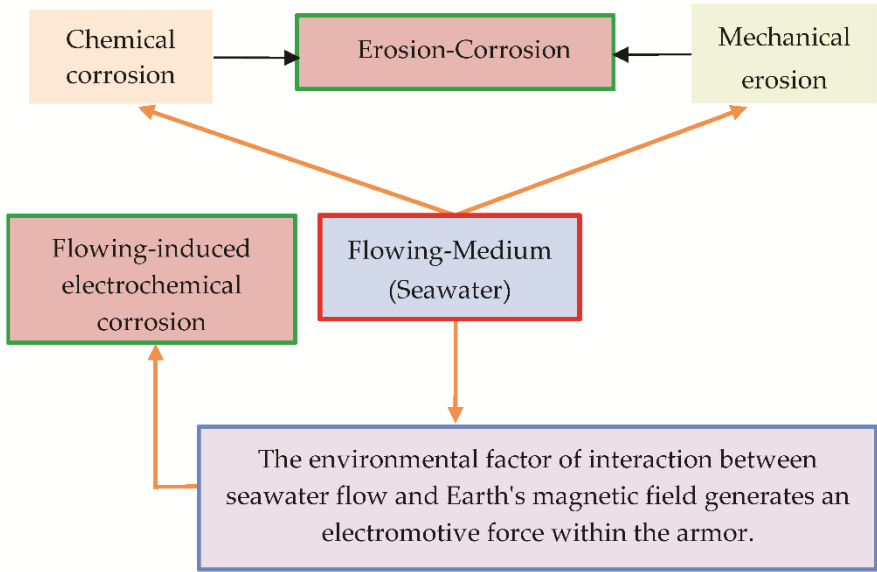


Figure 23. The schematic illustration of the interaction involved in the corrosion of armor in a marine environment.

- Erosion-corrosion of armor in a marine environment follows this fundamental pattern:
1. Corrosion leads to the formation of metal oxides and hydroxides on the surface.
 2. The swift seawater flow over the metal surface dislodges oxides and hydroxides, thereby exposing the underlying fresh metal.
 3. The exposed fresh metal surface corrodes.
 4. The above process (1) to (3) repeats continuously from beginning to end until the metal component fails.

5.2.4. Seawater Moving Induced Corrosion

Erosion corrosion rate (E) and fluid velocity (v) are related through equation (3): where K is the material constant that depends on particle size and impact angle, and n is the velocity exponent [3].

$E = K v^n$ (3)

After examining the extent of steel corrosion in seawater as a function of seawater velocity, the experimental results were reported in reference [4]. Figure 24 shows the experimentally derived steel corrosion rate as a function of seawater velocity and demonstrates the validity of equation (3).

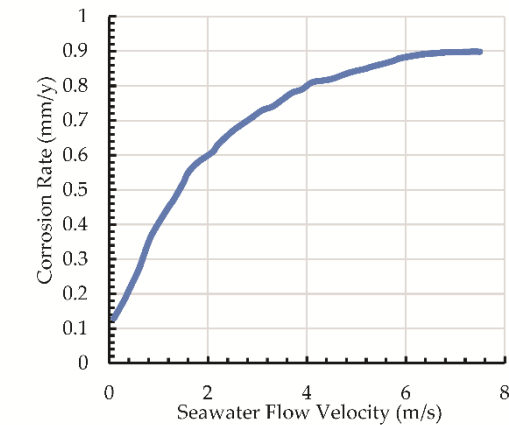
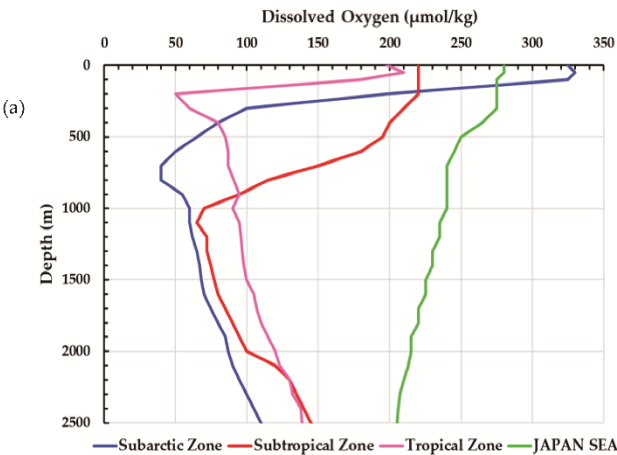


Figure 24. Effect of flow velocity on the corrosion rate of steel in seawater.

The experimental results confirm that increasing seawater flow velocity accelerates oxide wear on the armor surface and increases the supply of dissolved oxygen to the exposed fresh metal in a corrosive environment, thereby promoting corrosion.

5.2.5. Dissolved Oxygen

Dissolved oxygen, as an oxidant, markedly influences the corrosion of steel in marine environments. Figure 25 shows dissolved oxygen concentrations at various depths across four distinct locations surrounding Japan [36]. Across all locations, surface waters at depths of 0–200 meters consistently exhibit high dissolved oxygen concentrations. In the Japan Sea, which branches into the Tsugaru Warm Current, dissolved oxygen concentrations are increasing at multiple depths.



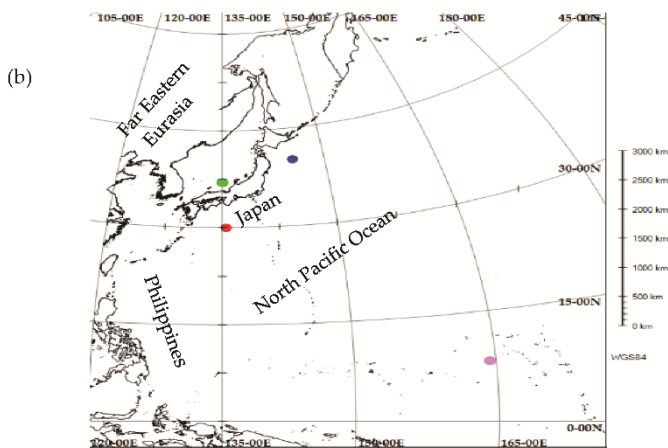


Figure 25. (a) The correlation between dissolved oxygen levels and water depth in the Northwestern Pacific Ocean, and (b) the sampling site.

5.3. Analysis of Corrosion in Armor

During cable loading and laying on ships, mechanical damage to the armor surface is inevitable due to friction with transport equipment, onboard laying mechanisms, buried equipment, and the ship’s hull. Corrosion from seawater exposure occurs at damaged sites, and the rate of seawater flow significantly influences the corrosion rate.

5.3.1. Corrosion Classification

Corrosion is classified by mechanism, as shown in Figure 26.

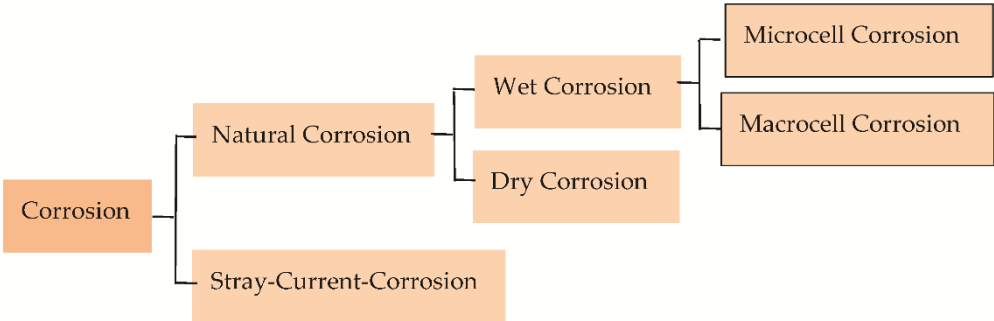


Figure 26. Diagram of corrosion classification.

5.3.1.1. Microcells and Macrocell Corrosion

Corrosion of armor in seawater can be classified into two types based on the spatial configuration of the electrochemical cell. Figures 27 and 28 show the Segmented armor and corrosion cells of microcell and macrocell corrosion in a marine environment.

The initial category is designated as microcell corrosion, characterized by randomly distributed microscopic anodic and cathodic regions that coexist in proximity across the armor surface. The second type is designated macrocell corrosion. It manifests when the chloride-ion concentration varies significantly along the armor. Both microcell and macrocell activities contribute to the overall corrosion process. Notably, literature reports that macrocell corrosion often occurs in the vicinity of damage to existing armoring [37].

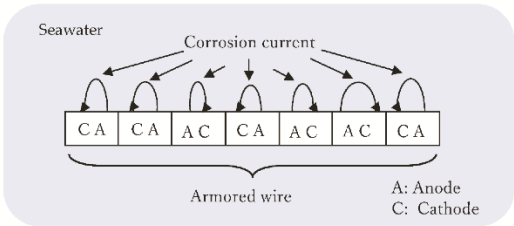


Figure 27. Microcell corrosion development in a marine environment.

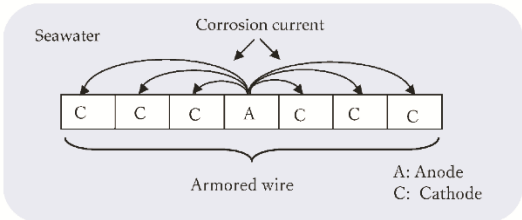
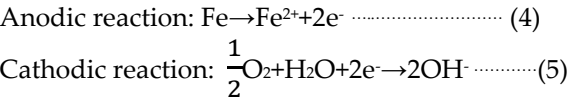


Figure 28. Macrocell corrosion development in a marine environment.

Figure 29 presents a schematic illustrating the progression of macrocell corrosion within a mechanically damaged region of an armor surface in a marine environment.

Stage 1

When a mechanically damaged area on the surface of armor is immersed in seawater, both anodic and cathodic reactions begin in and around the affected area. Equations (4) and (5) elucidate the anodic and cathodic reactions associated with steel corrosion in seawater that has dissolved oxygen.



Stage 2

When the increased electrical conductivity of the seawater electrolyte significantly reduces the circuit resistance within the corrosion cell, it accelerates corrosion, highlighting the complex interplay between electrical properties and material degradation. As a result, the corrosion area expands.

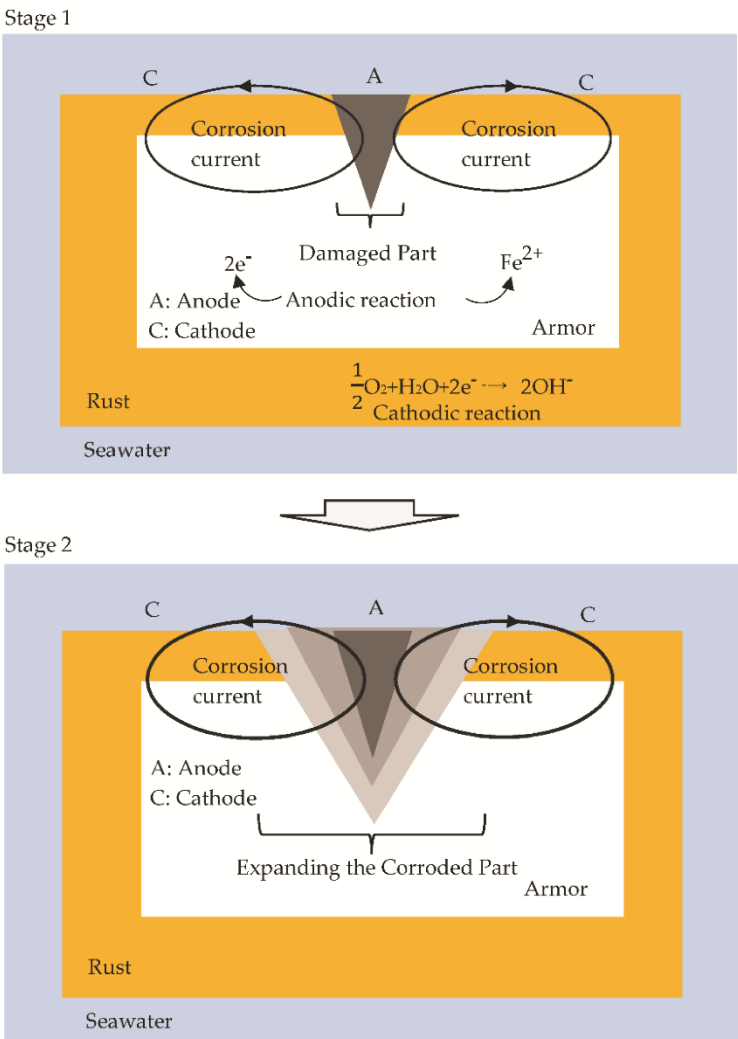


Figure 29. Schematic stages of Macrocell corrosion development in a marine environment.

5.4. Case Study on Corrosion of Armor

To elucidate the corrosion of armor caused by multiple environmental factors, we will conduct metallurgical analyses, including visual inspections and scanning electron microscopy (SEM) of thinned regions, on recovered SAM cables from maintenance activities.

5.4.1. Condition of Recovered Cable

The appearance of recovered armored cables can be a clear indication that armor corrosion can cause physical degradation. During maintenance activities, the cables are recovered about 7 km offshore in Ibaraki Prefecture, northeast of Tokyo. A distinctive feature of the armor of the recovered cable is that only the upper segment is progressively thinned due to corrosion wastage. Table 16 provides an overview of the recovered cable.

Table 16. Details of Recovered Cable.

Item	Description
Cable Types	SAM
Armor wire	$\varphi 5.0 \times 18$ Galvanized steel wires.
Laying method at the construction stage.	Surface lay
Number of years since system completion.	23
Seabed Feature	Sand and flat
Water depth (m)	219
Seawater flow velocity throughout the year.	Approximately 1 knot [38].

5.4.2. Corrosion Behavior Observed by Visual Inspection and SEM

The recovered cable and the sections with reduced armor thickness due to corrosion are illustrated in Figure 30.

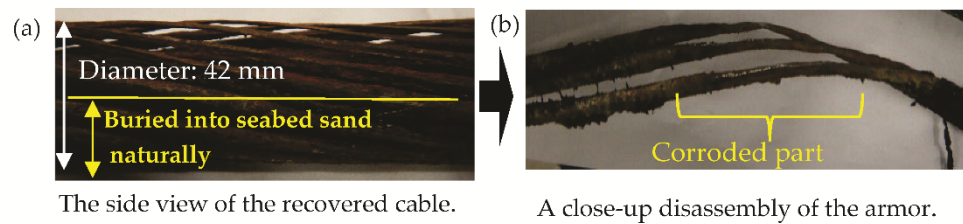


Figure 30. (a, b) Detail view of the recovered cable.

Since it was not possible to distinguish the upper and lower surfaces of the recovered cable on the seabed based on its appearance, the side exhibiting thinning of the armor wire due to corrosion was presumed to be the upper surface and was subsequently analyzed.

As shown in Figure 30(a), only the upper surface of the armor is corroded. The lower surface cable is believed to have been partially buried naturally in the seabed sand due to its weight in water and to have been protected from seawater flow. One possible cause of corrosion is environmentally coupled multi-factors, such as wet corrosion, seawater flow, and the Earth’s magnetic field. Conversely, as shown in Figure 30(b), the armor diameter is thinning. Figure 31 presents the measurement results for the armor’s outer diameter, including the thinned region.

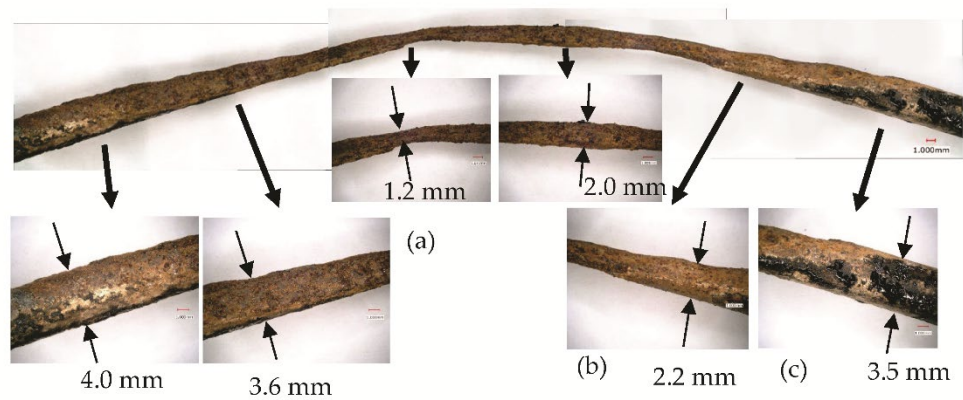


Figure 31. A close-up of the armor with its diameter thinned in places.

Figure 32. illustrates cross-sectional observations obtained through SEM of three regions: (a) with a significant thinning, (b) with a moderate thinning, and (c) with a minimal thinning in Figure 31.

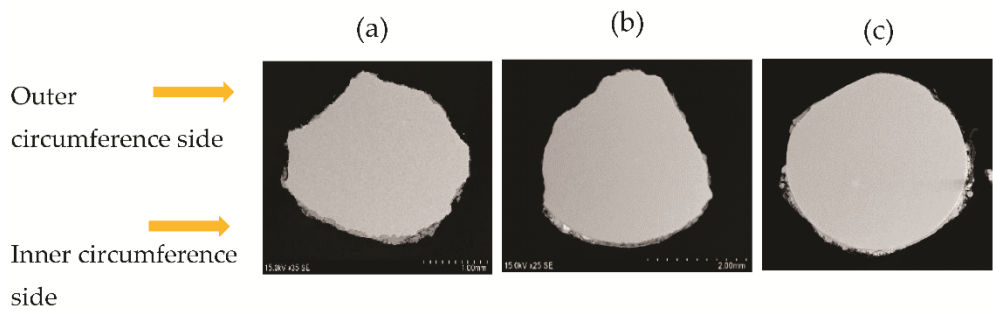


Figure 32. Compares corrosion progression as observed by SEM.

5.4.3. Considerations of Corrosion Behavior Observed by SEM

1. The progression of corrosion is contingent upon the overall geometry of each cross-section. One side corrodes and loses material, whereas the other retains its original armor configuration. This corrosion form suggests that corrosion predominantly occurs on one particular side of the armor surface.
2. The less corroded side has a zinc plating layer that inhibits further corrosion.
3. Furthermore, the triangular corrosion shapes observed on the cross sections of the armors are thought to be due to the proximity of adjacent armors.
4. Therefore, armor corrosion is thought to occur when the outer layer of the bitumen-impregnated polypropylene yarn degrades or is damaged, allowing seawater to penetrate and corrode the galvanized surface. As a result, the corrosion protection layer is partially corroded by seawater, accelerating the corrosion of the armor substrate.
5. As corrosion progresses, the armor’s mechanical strength decreases, leading to its failure.

5.5. Equivalent Circuit of Armor Regarding Corrosion

Figure 33(a) depicts a system configuration in which both buried and unburied segments are integrated using armored cable and repeaters. Figure 33(b) illustrates the cable installation, including the surface-laying method used in a steep-slope region of the seabed. Figure 33(c) shows the equivalent circuit of the armor. The repeater insulates the electrical continuity of the armor between subsequent sections.

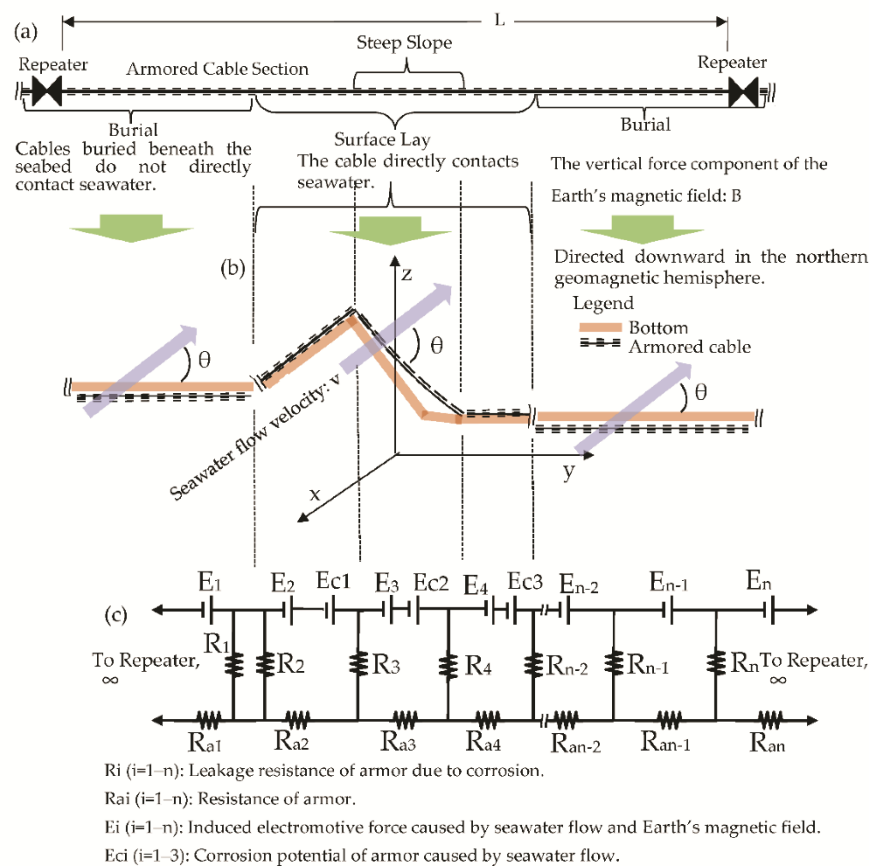


Figure 33. (a) Diagram of an armored cable section, (b) the cable installation including surface laying on a steep slope region, and (c) the equivalent circuit of armor between the repeaters.

The electromotive force, denoted as (E), is generated throughout the armor of cable section between repeaters due to the interaction of seawater flow with Earth’s magnetic field’s vertical component—an effect explained by Faraday’s law of electromagnetic induction—and can be approximated using the following equation (6) [5].

$E = E_1+E_2+E_3+E_4+E_{n-2}+E_{n-1}+E_n = B L v \sin \theta$ (6)

where

- E : Induced electromotive force (V)
- B : Vertical component of Earth’s magnetic field (T)
- L : Cable length between repeaters (km)
- v : Seawater flow velocity (m/s)
- θ : Angle between the cable and the seawater flow direction (degrees)

It was confirmed that seawater flow velocity contributes to armor corrosion, as evidenced by equations (3) and (6).

5.5.1. Comparison of the Buried and Surface Lay Sections

(1) Cable Burial Section

Since the armor does not come into contact with dissolved oxygen in seawater due to being insulated by seabed soil, $E_{ci} \approx 0$. As a result, armor corrosion is significantly minimized. Consequently, the leakage resistances of armor R_1, R_{n-2}, R_{n-1} , and R_n are elevated. As a result, minimizing the corrosion current in each circuit. This analysis shows that leakage resistance is a key factor in the progression of corrosion.

According to civil engineering reports, the resistivity of seabed soil beneath the seabed at depths of 14 to 20 meters is 50 (Ω -cm) in Tokyo Bay, Japan [39]. In contrast, the resistivity of seawater ranges

from 20 to 30 (Ω -cm) (see Table 15). This consideration clearly shows that the armor of buried cables is not susceptible to corrosion, and it supports the observation that the armor of buried cables recovered during maintenance activity is free of corrosion.

(2) Surface Laying Section

Electromotive forces, E_i , resulting from seawater flow and the Earth’s magnetic field, and the corrosion potential, E_{ci} , caused by seawater flow, are induced in the armor. Furthermore, R2, R3, and R4 are approximately zero due to armor corrosion, resulting in short circuits. Furthermore, the persistent flow of corrosion current through each circuit accelerates the corrosion process.

5.6. Expected Service Life of Armor Based on a Proven Record

We will examine the lifespan of a single armored cable surface-laid between Nemuro, at the eastern tip of Hokkaido, Japan, and Kunashiri Island (a Distance of 38.2 km), a Japanese territory at the time, in the 1900s. Figure 34 shows the geographical route of the Nemuro-Kunashiri Island cable.

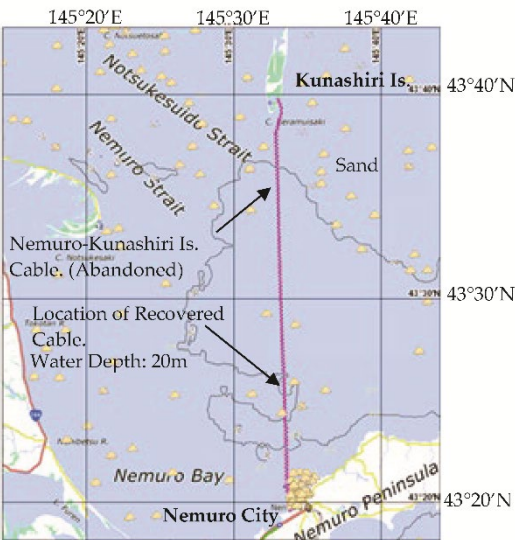


Figure 34. Route of the Abandoned Nemuro-Kunashiri Island cable [15].
Approximate location: see to Figure 9.

Table 17 shows the transition of the Nemuro-Kunashiri Island cable.

Table 17. Transition of the Nemuro-Kunashiri Island cable.

Event	Date	Remarks	References
Installation	1900, September		[40]
End of operation	1945, About September	After World War II ended, the cable was intentionally cut and left abandoned.	
Partial cable recovery	1999, January	Location : 10 km north of Nemuro, Water Depth: 20 m	[41]

Figure 35 illustrates the structural appearance and cross-section of the recovered cable.

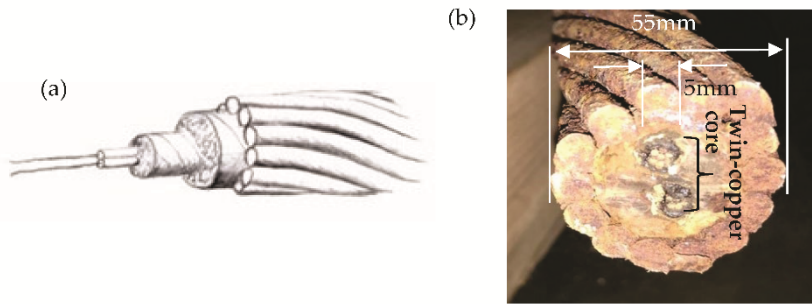


Figure 35. Details of the recovered Nemuro-Kunashiri Island cable.
(a) Structural Appearance, Courtesy of Mr. Hiroaki Kubo in Hokkaido, Japan.
(b) Close-up of the cross-section and dimensions, courtesy of Nemuro City Hall in Hokkaido, Japan.

5.6.1. Considerations on Corrosion for Armor

The cable has a 55 mm diameter, and the armor consists of 14 steel wires, each 5 mm in diameter. Rust covers the entire surface of the armor due to corrosion. There is no evidence of mechanical wear or erosion corrosion. This is because the seawater flow velocity near Nemuro Strait, where the submarine cable in Figure 34 is located, remains below 0.5 knots year-round [42]. The seabed is flat and sandy. This suggests that the submerged cable’s weight will bury almost all of it. The gentle seawater flow likely allowed corrosive materials to accumulate on exposed armor sections, or it minimized corrosion from oxygen concentration cells. In both cases, the progression of corrosion was significantly slowed.

5.7. Evidence-Based Expectation of Armor Longevity

Upon analyzing armor thinning due to corrosion across three cases in the marine environment, as discussed in Sections 3, 5.4, and 5.7, it was determined that the seawater flow velocity substantially affects long-term durability. Figure 36 illustrates the relationship between the velocity of seawater flow and armor durability, as verified above. In the future, increasing the sample size will enable more accurate performance charts.

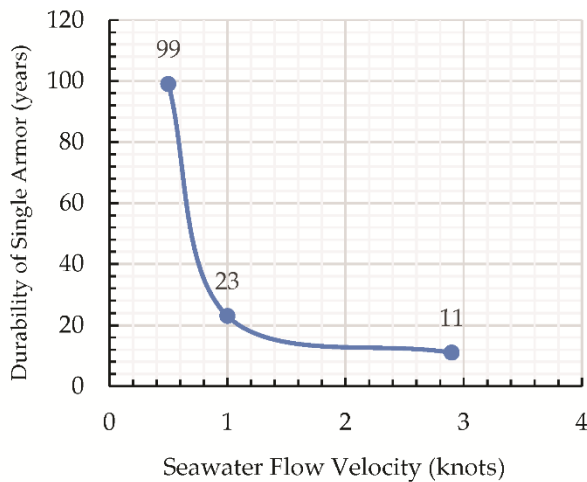


Figure 36. Long-term durability of single armor against seawater flow velocities, based on verification results.

To ensure reliable performance in the challenging marine environment, the International Telecommunications Union (ITU) specifies a 25-year designated lifetime for the submerged segment (also known as the “wet plant”) [43]. This standard is based solely on the reliability of the parts and

components that constitute the system and does not consider environmental factors. It is challenging to forecast the external forces—such as natural disasters or industrial activities—that may influence cable failures. Based on this, when applying the ITU standard for designed lifetime to the SAM cable exposed on the seabed and considering environmental factors, it is recommended that the seawater flow velocity should be approximately 1.0 knots or less, as illustrated in Figure 36.

5.8. Proposed Measures for Armor Corrosion and a Comparative Analysis of Their Economic Impact

Given that it is impractical to eliminate the environmental factors responsible for armor degradation and corrosion, Table 18 outlines the fundamental and mitigation measures, along with their associated cost impacts.

Table 18. Comparison of Measures for Degradation of Armor and Cost Impact.

Classification of Strategies	Illustrations of Specific Measures	Cost impact	Remarks
Fundamental	a. Change armor to economical non-magnetic materials.	High	Candidate material: Fiber Reinforced Plastic (FRP) A new development is needed.
	b. Implement the cable burial method.	Ditto	---
	c. Change the cable routing.	Ditto	Seawater flow velocity: Less than 1.0 knots.
Mitigative	a. Apply a double armored cable to increase the armor's mass.	Low	Methodologies for practical repair work in SAM cable section.
	b. Apply a sheath to the armor to block seawater contact.	Ditto	In areas with strong currents or at the shoreline, a polyurethane sheath protects the armor.
	c. Cable protection by a cast-iron pipe.	---	The diver's working depth is limited to 30 meters.
	d. Regular visual inspection by a diver.	---	

6. Conclusion

Using empirical evidence and scientific methods, this research, through hypothesis validation and data analysis, elucidated the following influence of marine environmental factors on OFS cable durability.

- (1) Environmentally Coupled Multi-Factor Corrosion of Armor, Except Composition of Seawater
- The velocity of seawater flows along the armored OFS cable.
 - The electromotive force induced in the armor by the ocean current crossing the vertical component of the Earth’s magnetic field.
- (2) A factor in extending the lifespan of unarmored OFS cable
- The fundamental composition and thickness of the deep-sea sediments in the oceanic basin.

These findings will provide a solid foundation for future development of undersea communications infrastructure, enabling reliable data transmission and secure information exchange, strengthening protection against environmental risks, and directly strengthening critical economic and social infrastructure. Finally, we anticipate that increased interdisciplinary research will foster the development of more reliable, stable, and cost-effective undersea digital communication infrastructures that remain operational beyond their designed lifetimes in marine environments.

Author Contributions: Conception and design, methodology, data collection, formal analysis, investigation, and writing - original draft preparation, review, and supervision, Y.O. The Author has read the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Request to the author of this article.

Acknowledgments: During the preparation of this manuscript, KDDI Cable Ship & Subsea Engineering Inc. (KCS), based in Kawasaki-shi, Kanagawa Prefecture, Japan, graciously provided an extensive collection of valuable maintenance records related to their cable maintenance operations. We also express our gratitude to Nemuro City Hall in Hokkaido and to Mr. Hiroaki Kubo, a resident of Nemuro, for providing materials on the Nemuro-Kunashiri Island cable.

Conflicts of Interest: The author declares no conflict of interest.

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