THE CHALLENGES TO THE SEABED CRITICAL INFRASTRUCTURES

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Abstract. The article presents a study in the area of critical maritime infrastructure protection, pointed on the underwater domain and safeguarding of seabed critical infrastructures which are vital for global communications, energy supplies, and international economies in the modern security environment. The objective of the study is to identify the key challenges to the protection of the seabed critical infrastructure by identifying potential risks and threats and to analyze the vulnerabilities of the security system in a legal, procedural and technological terms.

The article is structured in the same logical way, which leads to multivariate analysis and classification. The main findings are based on the understanding that the resilience of critical infrastructures is characterized by overcoming a complex set of technical, legal, geopolitical and environmental challenges, which requires joint international efforts and advances in technology to improve monitoring, maintenance and protection strategies.

Keywords: Seabed Critical Infrastructures, challenges, protection, threats, technological innovation, legal framework

1. Introduction

The Seabed Critical Infrastructure (SCI) encompasses essential installations situated on or beneath the ocean floor, including submarine communication cables, energy pipelines, and renewable energy facilities. This infrastructure plays a pivotal role in the modern digital economy and global energy supply. Submarine communication cables carry around 95% of global internet traffic, while underwater oil and gas pipelines ensure the continuous flow of energy resources to meet global demand. Moreover, with the rise of renewable energy, offshore wind and tidal power installations are becoming increasingly significant.

However, this infrastructure is largely unseen and often taken for granted, yet its disruption can have far-reaching consequences, including economic, social, and security impacts. It can be defined that SCI faces several challenges due to its remote location and exposure to natural, technological, geopolitical, and environmental risks. This study explores these challenges in detail, offering insights into the potential threats to seabed infrastructure and identifying solutions that could enhance its resilience.

2. Types of Seabed Critical Infrastructure

The Seabed critical infrastructure refers to the key systems and installations located on or under the ocean floor that support vital sectors such as energy, communications, and transportation. These infrastructures are essential for modern society and global economies and includes submarine communication and power cables, offshore oil and gas pipelines, renewable energy infrastructure and emerging technologies.

2.1 Communication infrastructure.

Submarine communication cables are the backbone of the internet, facilitating the transfer of data across oceans. Modern submarine cables contain optical fibres, and consist of multiple pairs of fibres and can carry approximately 98% of all manner data globally, including private communications (e.g. email and messaging services), banking data, stock market data, medical data, scientific data, government communications, traffic between data centers, and video streaming (Burnett, 2013). In addition, they are largely owned and operated by the private sector and routes have generally been determined by commercial considerations (as ships follow SLOCs). The vulnerability of these cables to external threats, both natural and man-made, makes them a critical focus of security efforts.

2.2 Energy infrastructure.

Underwater pipelines are used to transport oil and gas from offshore drilling platforms to onshore processing facilities. Examples include the Nord Stream pipelines that transport natural gas from Russia to Europe and the Trans-Mediterranean Pipeline connecting Algeria to Italy. These pipelines are susceptible to both environmental and human threats, from natural disasters to sabotage.

Renewable Energy Infrastructure Offshore wind farms, such as those in the North Sea and off the coast of the United States and China, represent a significant portion of renewable energy infrastructure. Tidal energy, like the Seagen project in Northern Ireland, harnesses the energy of ocean tides but requires robust seabed installations to ensure long-term operation. The construction and maintenance of these structures are complex, especially in rough sea conditions.

New technologies such as deep-sea mining for rare earth minerals (involves the extraction of valuable minerals and resources from the ocean floor, specifically from areas rich in polymetallic nodules, sulfide deposits, and cobalt-rich crusts) and autonomous sensors for environmental monitoring are increasing the demand for secure and resilient seabed infrastructure. These minerals are critical for industries like electronics, renewable energy, and high-tech manufacturing. These new ventures introduce additional complexities, including ethical and environmental concerns.

2.3 Transportation infrastructure.

Subsea tunnels and railways, such as the Channel Tunnel connecting the UK and France, facilitate rapid, uninterrupted transportation beneath the ocean floor. These tunnels are monumental engineering feats, enabling the transport of people, vehicles, and goods between continents without relying on maritime or air transport. The construction of these tunnels involves advanced engineering techniques to overcome challenges like water pressure, geological instability, and environmental protection.

Ports are the hubs of global trade, and many modern ports require extensive seabed infrastructure to accommodate the needs of mega-ships and modern logistics operations. Underwater foundations and dredging systems allow for the expansion of port facilities, the construction of artificial harbors, and the installation of critical docking equipment. Additionally, the construction of offshore ports in deep waters is becoming more common to manage the increasing volume of international trade.

3. Challenges to SCI

Seabed critical infrastructure such as submarine communication cables, pipelines, and offshore energy installations is fundamental to global communications, energy transmission, and economic stability and faces various challenges that threaten its integrity and functionality. These challenges can be categorized into natural, human-induced, and technical/operational threats. A risk

assessment of this infrastructure is essential to understand the vulnerabilities it faces, the potential impacts of disruptions, and the mitigation strategies required to safeguard these vital assets.

3.1 Natural challenges.

This kind of challenges arises from the ocean's dynamic and often unpredictable environment, and can be triggered by natural events, such as earthquakes, tsunamis, and ocean currents.

3.1.1 Seismic Activity and Tsunamis.

Tectonic activity can sever cables or rupture pipelines, leading to major outages (Meracheva et al. 2022). For example, the 2006 Hengchun earthquake off the coast of Taiwan resulted in the severing of multiple undersea cables, causing widespread disruption to internet services across Asia. Tsunamis and underwater landslides, triggered by seismic events, can similarly displace or damage infrastructure on the seabed.

3.1.2 Submarine Landslides and Erosion.

Submarine landslides, like those seen off the coast of Norway in the North Atlantic, can damage or displace seabed infrastructure. The collapse of large sections of underwater slopes can sever pipelines or communication cables, as happened in the Storegga Slide event about 8,000 years ago.

3.1.3 Ocean Currents, Storms, and Ice Flows

Seabed infrastructure is constantly exposed to marine hydrodynamics, such as ocean currents, waves, and tides, which can lead to both immediate and long-term damage. Ocean currents and storms pose ongoing challenges to offshore wind turbines and floating infrastructure. In areas like the North Atlantic and Arctic seas, ice flows and extreme storms can cause structural damage to pipelines, cables, and renewable energy installations.

3.1.4 Marine Life.

Large marine animals, such as sharks or whales, may accidentally interact with cables, while biofouling (marine organisms attaching to surfaces) can degrade equipment over time. Some bacteria and microorganisms in deep-sea environments can produce chemicals that accelerate the corrosion of metal components, such as pipelines. Sulfate-reducing bacteria (SRBs), for instance, produce hydrogen sulfide, which can lead to metal corrosion in pipelines.

It can be summarized that these natural challenges make seabed critical infrastructure vulnerable to damage, demanding robust design, material selection, and regular monitoring to ensure longevity and reliability. Enhanced mapping, predictive modeling, and cooperation between industries are vital to mitigate these risks in the future.

3.2 Human-Induced Challenges

Human activity poses significant risks to seabed critical infrastructure. Fishing and trawling, shipping traffic, and offshore exploration, are all potential sources of damage.

3.2.1 Fishing and Trawling Operations.

Commercial fishing, particularly bottom trawling, is a significant threat to undersea cables. Due to many undersea fiber-optic cables are laid in shallow waters close to coasts, trawlers, while dragging large and heavy nets across the seabed, can inadvertently catch and damage it. The repeated dragging of nets or fishing gear can lead to cuts or abrasions, interrupting data

transmission or causing total cable failure. For example, the East African Submarine Cable System (EASSy) faced disruptions due to fishing equipment damage in the early 2010s.

Oil and gas pipelines, especially in continental shelves, are also vulnerable to bottom trawling. If a pipeline is damaged, it could lead to leaks, which would be both environmentally and economically devastating.

3.2.2 Shipping Traffic.

Dense maritime traffic increases the risk of vessel collisions, which can damage both surface and underwater infrastructure. Shipwrecks, while less frequent in modern times, can have devastating consequences on undersea installations, especially pipelines. In addition, anchors, especially from large commercial vessels or tankers, can weigh several tons and are capable of dragging across the seabed, cutting or rupturing undersea cables and pipelines. For examples in 2021, the South East Asia-Middle East-Western Europe 3 (SEA-ME-WE 3) undersea cable, one of the longest in the world, was damaged due to an anchor dragging incident near the coast of Singapore, causing internet outages in several countries. Another case is California Oil Spill (2021) when an anchor strike from a commercial ship was suspected to have caused the rupture of an undersea pipeline off the coast of Southern California, leading to a major oil spill.

3.2.3 Offshore Energy Developments.

Offshore oil and gas drilling poses a risk to existing infrastructure due to the proximity of new developments to existing cables and pipelines. The construction of new offshore energy installations, including oil rigs, wind turbines, or underwater mining operations, can disturb nearby infrastructure (Fröberg & Herrmann, 2020). In some areas, for example the North Sea, which is dense with both energy infrastructure and communication cables, there is higher risk of incidents where undersea cables can be accidentally severed during offshore oil platform construction or maintenance..

In addition, offshore mineral exploration for rare earth elements has the potential to interfere with cables or pipelines that already exist in deep ocean regions.

In common human activity, often unintended, poses another significant risk (Burgherr & Hirschberg, 2014). Commercial fishing operations, particularly bottom trawling, frequently damage undersea cables, while shipping accidents, such as ships dropping or dragging anchors, can destroy critical infrastructure. Such incidents are common in busy maritime routes, where the concentration of vessels increases the risk of accidental damage. Proactive measures such as stricter regulations, advanced monitoring systems, and international cooperation are essential to safeguarding these assets. As human activity in the ocean continues to grow, especially with the expansion of offshore wind energy and deep-sea mining, the risks will need to be managed with even greater precision.

3.3 Geopolitical and Security Challenges

The protection of seabed critical infrastructure is becoming an increasingly complex challenge due to evolving geopolitical tensions and security threats. Territorial disputes, resource competition, state-sponsored sabotage, terrorism, and cyber-attacks all present significant risks to the stability of global seabed networks (Ridley, 2017).

3.3.1 Sabotage, Espionage and State-Sponsored Attacks.

As global reliance on undersea infrastructure grows, these installations have become strategic targets for sabotage by state and non-state actors. Attacks on undersea cables or pipelines can disrupt internet access, financial transactions, and energy supplies, making them a potential weapon in geopolitical conflicts. For example, in September 2022, explosions occurred on the Nord Stream 1 and 2 pipelines in the Baltic Sea, which connect Russia and Germany. These incidents highlighted the vulnerability of subsea energy infrastructure to sabotage and caused significant energy supply disruptions in Europe, especially amid the Russia-Ukraine conflict. Another case is *Operation Ivy Bells* during the Cold War, when the United States and the Soviet Union engaged in covert operations tapped into each other's undersea communication cables for intelligence gathering. Today, similar risks persist, with modern states potentially targeting undersea cables for surveillance or disruption. In addition, there have been numerous incidents of submarines from various nations being detected near sensitive seabed infrastructure for potential espionage, such as the interception of data transmitted through submarine cables, which poses a significant risk to national security and international relations.

3.3.2 Cyberattacks.

As seabed infrastructure becomes increasingly integrated with digital monitoring and control systems, the risk of cyberattacks has grown. Hackers can target the digital management systems that oversee the operations of undersea cables, such the Supervisory Control and Data Acquisition (SCADA) systems case, energy platforms, or pipelines, leading to disruptions without physically damaging the infrastructure. Another example is the disrupting satellite or GPS communication for vessels increasing the risk of accidental collisions and damages. This is particularly concerning in regions where geopolitical tensions are high, like the South China Sea.

3.3.3 Territorial disputes and Exclusive Economic Zones (EEZ) conflicts

Many undersea cables and pipelines cross areas of disputed waters or pass through the Exclusive Economic Zones (EEZs) of different countries. This creates a risk of conflicts over jurisdiction, access, and control, complicating the maintenance and expansion of seabed infrastructure. For example, South China Sea is a hotspot for disputes between China and its neighbors (the Philippines, Vietnam and Malaysia) over control of strategic maritime zones. Numerous undersea cables pass through this area, making it a potential flashpoint for geopolitical tensions.

As the Arctic ice melts, countries like Russia, the United States, and Canada are increasingly interested in exploring new routes for undersea cables through the Arctic Ocean. This opens up opportunities for faster data transmission between North America, Europe, and Asia but also raises tensions over control and access rights.

It can be summarized that geopolitical and security risks to seabed critical infrastructure are multifaceted, encompassing direct physical threats, digital vulnerabilities, and complex international disputes. The consequences of damage or disruption to this infrastructure can ripple through global communications, energy supplies, and economic stability. Effective mitigation requires a combination of technological innovation, strategic international cooperation, and robust security measures. As the global reliance on undersea networks grows, managing these risks becomes ever more critical.

3.4 Regulatory and Legal Challenges

Despite its importance, protecting the seabed critical infrastructure presents numerous regulatory and legal challenges due to the complex, cross-jurisdictional nature of the marine environment, evolving threats, and the limitations of current international and national laws.

3.4.1 Jurisdictional ambiguities in international waters - legal gaps in High Seas.

One of the most significant legal challenges to protecting seabed infrastructure is the ambiguity surrounding jurisdiction in international waters. Under the United Nations Convention on the Law of the Sea (UNCLOS), different maritime zones (territorial seas, exclusive economic zones, and high seas) have varying legal rules regarding sovereignty, exploitation rights, and responsibilities for protecting infrastructure. UNCLOS defines countries' rights over the High seas: *Beyond 200 nautical miles, no state has sovereignty, and international law governs activities*. Infrastructure located on the high seas lacks clear protective mechanisms under international law. UNCLOS provides freedom to lay cables and pipelines, but enforcement and protection responsibilities remain unclear (Bourrel & Rochette, 2019). In accordance with UNCLOS Article 113 (Cable Protection) states are required to create domestic laws penalizing those who "break or injure a submarine cable." However, these laws are only enforceable within a state's territorial sea or EEZ, and enforcement on the high seas remains underdeveloped (Oude Elferink, 2009). As well acts of piracy or sabotage in international waters are difficult to prosecute due to these jurisdictional gaps, and no single entity is responsible for coordinating a global response.

3.4.2 Limited international legal protections

Despite the critical role of undersea infrastructure, international law provides limited protections beyond installation rights, leaving much of the security responsibility to individual nations and industry players. The International Maritime Organization (IMO) issues guidelines to prevent accidental damage to seabed infrastructure, such as advising maritime traffic to avoid areas where critical cables and pipelines are laid. However, IMO guidelines are non-binding and primarily focus on accidental damage from ships rather than intentional attacks. Implementation varies between states, leading to inconsistent adherence, particularly in regions with heavy maritime traffic, such as the Mediterranean and South China Sea.

There is limited coordination between states for cross-border protection. Damage caused by fishing or anchoring in one country's EEZ can affect neighboring countries due to the interconnected nature of undersea cable systems.

The Budapest Convention on Cybercrime (2001) addresses illegal access to and interference with infrastructure systems, including those related to critical infrastructure like pipelines and undersea cables. However, it focuses primarily on cyber-attacks and data theft, rather than physical protection. The convention is not universally adopted, and key global powers, such as Russia and China, are not signatories, leading to gaps in international cooperation on cybersecurity issues related to seabed infrastructure.

3.4.3 National regulatory gaps and coordination challenges

National laws also face challenges in adequately protecting seabed infrastructure. National legislation is often fragmented, with different countries adopting inconsistent rules for managing and safeguarding seabed infrastructure, which can lead to coordination difficulties in cross-border regions. Countries with extensive maritime infrastructure, such as the UK, the US, and Norway, have implemented robust legal frameworks to protect their seabed assets. However, other nations may lack comprehensive laws or regulatory resources to enforce infrastructure protection,

particularly in developing regions. For example, the United States has specific laws under the Submarine Cable Protection Act (1956) and the Outer Continental Shelf Lands Act (OCSLA) to protect cables and energy installations. However, many countries, particularly small island nations, lack similar comprehensive protections, creating vulnerabilities in global networks.

The rapid expansion of offshore wind farms, tidal energy installations, and underwater solar arrays presents new regulatory challenges. Existing laws often focus on traditional infrastructure, such as oil pipelines and communication cables, but may not fully cover newer technologies. In the North Sea, regulations governing offshore wind farms remain a patchwork of regional agreements and national laws, leading to gaps in protection, especially as these farms increasingly rely on smart grids and undersea energy cables to connect to the mainland.

4. Potential Solutions and Future Outlook.

Due to the underwater environment presents unique challenges, such as extreme pressure, temperature fluctuations, and dynamic seafloor conditions, making the resilience of this infrastructure vital. In recent years, climate change has further intensified the need for robust technologies that can withstand more frequent and severe oceanic conditions. Advancements in materials science, such as the development of corrosion-resistant alloys, and improvements in deep-sea robotics could enhance the durability and reliability of seabed infrastructure.

4.1 Technological innovations in Seabed infrastructure protection.

The integration of emerging technologies into the protection of critical maritime infrastructure is paramount in addressing current and future security challenges. These technologies aim to close existing capability gaps and enhance the resilience of seabed critical infrastructure. Key technological solutions encompass advanced sensors, autonomous systems, specialized sonar systems and cybersecurity measures, which together form an integrated defense mechanism for maritime critical infrastructure (Fridbertsson, 2023). One key innovation is the development of subsea monitoring systems that utilize sensors to provide real-time data on infrastructure health. These systems help in early detection of issues such as corrosion or structural weakness. As well, implementation of effective automated Command and Control (C2) systems is essential for responding to threats to critical seabed infrastructure. These systems integrate data from multiple sensors, unmanned vehicles, and surveillance platforms and use algorithms to prioritize threats and vulnerabilities (He et al., 2020) and optimize response times, ensuring that human operators have the most relevant information when making security decisions (Klein, 2018).

4.2 International cooperation on maritime laws and security frameworks.

International cooperation on maritime laws and the security frameworks surrounding seabed critical infrastructure is an increasingly important solution. With growing interests in offshore resources, communication cables, and underwater pipelines, states are motivated to collaborate on protecting these assets. This cooperation is crucial for maintaining stability, securing economic interests, and preserving the oceanic environment. The complexity of seabed governance requires an international regulatory framework to manage shared resources and infrastructure effectively. Coordinated efforts by global organizations, such as UNCLOS, can facilitate agreements on shared responsibilities and conflict resolution. Moreover, the creation of standardized safety protocols for seabed infrastructure would ensure that construction and maintenance follow best practices, reducing the risk of accidents and damage.

4.3 Sustainable practices

The shift towards sustainable practices in seabed operations is crucial for minimizing environmental impact. One solution is the adoption of environmentally friendly materials in the construction of underwater infrastructure, such as biodegradable coatings for cables. Additionally, integrating renewable energy sources such as tidal and wave energy can power seabed operations, making them more sustainable and reducing dependence on fossil fuels. Physical infrastructure must also be reinforced against natural disasters, such as earthquakes and tsunamis. Strengthening the material composition of cables and pipelines, along with advanced anchoring techniques, can mitigate the impact of these natural events.

4.4 Future Outlook

The future of seabed infrastructure lies in the integration of artificial intelligence (AI) (Smith & Warner, 2019) and machine learning technologies. These technologies can be used for predictive maintenance, where AI analyzes data from sensors to forecast potential failures before they occur. This can dramatically reduce downtime and repair costs.

Collaboration across the sectors addressing seabed challenges to require interaction between governments, industry, and academia. Joint research initiatives can lead to new breakthroughs in materials science, engineering, and environmental science, providing comprehensive solutions to existing and emerging problems.

Environmental considerations refer to climate change poses a long-term threat to seabed infrastructure, with rising sea levels and increased storm frequency leading to greater stress on these systems. Future infrastructure development must consider these changes and employ adaptive designs that can withstand dynamic ocean conditions.

5. Conclusion

Seabed critical infrastructure plays a foundational role in the global economy, energy supply, and communication networks. In the context of transportation, seabed infrastructure underpins not just physical movement, but also the critical systems that manage and monitor maritime transport routes. As global trade increasingly relies on maritime shipping, seabed infrastructure has become indispensable in ensuring the efficiency, security, and sustainability of supply chains.

The challenges facing seabed critical infrastructure are multifaceted, ranging from technological hurdles to environmental risks. However, with the implementation of innovative technologies, regulatory improvements, and sustainable practices, these challenges can be mitigated. Future research and policy initiatives will play a key role in shaping the resilience of seabed infrastructure, ensuring its continued functionality in an increasingly interconnected world. The future of international cooperation in maritime laws and the protection of seabed critical infrastructure will depend on adapting to technological changes, maintaining diplomatic efforts, and ensuring that all stakeholders, including private companies and international bodies, are engaged.

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