Dean&Francis

ISSN 2959-6157

From Detection to Action: Overcoming the Last-Mile Challenges in Seafloor Geohazard Monitoring

Zirui Hong[1, *]

[1]Department of North America International School, Shanghai, China
*Corresponding author: qdydnofcqy@lw.edu.kg

Abstract:
Submarine geohazards, including earthquakes, landslides, and volcanic activity, pose a series of complex threats to coastal communities and critical offshore infrastructure. While recent advances in seafloor monitoring technologies (e.g., distributed acoustic sensing, AI-enhanced seismometers) have improved detection capabilities, significant gaps persist between data collection and actionable warnings. This study identifies three critical issues: (1) hardware limitations, where 40% of deep-sea sensors fail within 18 months due to extreme pressures and corrosion; (2) data latency, with even advanced systems like Japan's DAS networks suffering 8–15-second delays in tsunami detection; and (3) institutional fragmentation, evidenced by 17 incompatible data formats across global OBS networks, leading to 22% data loss. We evaluate emerging solutions, from graphene-based pressure-resistant sensors to automated decision pipelines and prove how integrated systems could reduce warning times by 50% while cutting the unnecessary costs. The findings also point out an urgent need for standardized protocols and cross-sector collaboration to transform monitoring science into the more effective risk mitigation.

Keywords: Seafloor Geohazard Monitoring; Early Warning Systems; Sensor Reliability and Data. Integration.

1. Introduction

Oceans, which comprise of seventy one percent the Earth's surface, have been long intriguing yet unfathomable for researchers and publics. Admittedly, oceans themselves possess a crucial characteristic for people to identify, which is their duplicity. Oceans, historically, are beneficial for the global fishing industry. For instance, oceans contain plentiful aquatic creatures that fishers can capture. It does not just provide fishers with a sustainable means to earn the commercial benefits, but support individuals on an alimentary level: People, in this case, have wide access to marine nutrition and seafood, promoting the alimentary diversity. Oceans' duplicity is particularly more prominent in non-ideal circumstances, which hinders people's pursuit for the "aquatic perfectionism" and even threatens their well-beings, triggering marine anxiety.

Historically, marine geohazards represent one of the most complex and least understood challenges in the world. Unlike terrestrial disasters, submarine earthquakes and landslides occur in a mixing environment where fluid and solid meet, generating multi-phase threats that spread across the ocean basins. The 2011 Tohoku earthquake demonstrated it—within just twenty minutes, seafloor displacement triggered a tsunami that overtopped 10-meter seawalls, and seismic vibrations damaged the offshore infrastructure 200 kilometers from the epicenter [1]. Such disasters reveal that humans still lack the "fundamental" understandings in marine disaster detections: current systems detect less than 15% of precursory strain signals, while tsunami warning protocols often rely on incomplete divination data [2].

In the past few decades, there has been tremendous efforts but also paradoxical aspects in the development of deep-sea monitoring. For example, Distributed Acoustic Sensing (DAS) now achieves strain measurements at 5-meter intervals along fiber-optic cables [3], but 85% of subduction zones remain uncovered by permanent instrumentation [4]. Admittedly, autonomous seafloor detectors like Ocean Networks Canada's "NEPTUNE" array provide real-time fluid chemistry data, but their prohibitive deployment cost poses a huge burden on developing countries. Moreover, while machine-learning applications show some promises in distinguishing tectonic tremors from the shipping noise [5], training datasets remain biased toward Northern Hemisphere sites [6]. Such differences reveal a disconnection between technological capability and practical implementation.

Therefore, this study will confront those unresolved trouble during the marine investigations. First, we would integrate DAS-derived crustal strain patterns with hydrophone recordings of acoustic emissions to establish the first "multi-parameter" (which means multiple index measurements) early warning machinery. What's more, our framework demonstrates how shared sensor networks could cut monitoring costs for regions like Southeast Asian nations while still maintaining the "sub-90-second warning times" [7]. The novelty lies in our rejection of conventional approaches, instead treating the seafloor-atmosphere-human system as a triple continuum were crustal deformation links with continental phenomena. We're convinced that what emerges now is not merely another technical improvement, but also a paradigm shift in understanding marine hazards as a connective phenomenon. Where traditional models treat marine earthquakes and tsunamis as individual events, our findings demonstrate how fluid-mediated coupling transforms singular ruptures into cascading disasters—a reality demanding equally interconnected solutions. As submarine cable networks gradually expand into seismically active regions [8], this work provides the methodological foundation for next-generation monitoring systems that are as adaptive as the threats they're going to mitigate.

2. Research Status & Technological Progress

In recent years, significant progress has been made in high-resolution seafloor monitoring technologies, largely driven by the need to mitigate submarine geohazards. Among the most widely adopted systems, ocean-bottom seismometers (OBS) have become paramount for long-term seismic recording in submarine environments, offering precise measurements of crustal movements with deployment duration greater than a year in some cases [9]. However, such spatial coverage—typically limited to 10-20 km spacing due to a high deployment cost—leaves a critical gap in fault zone monitoring [10]. This limitation has promoted the rapid development of distributed acoustic sensing (DAS), which transforms existing submarine telecommunication cables into dense seismic arrays with meter-scale spatial resolution. Field tests along the Monterey Bay fault system demonstrate DAS's ability to detect seismic activities below a magnitude of 1.5, which would, previously, be unattainable with conventional OBS networks [11].

To complement these technologies, hydrophone arrays have emerged as crucial tools for capturing the acoustic signatures of non-seismic activities. The "NEMO-SN1" observatory in Mediterranean areas, for instance, has successfully identified the harmonic tremors at Campi Fergie's submarine vents 48 hours before the surface activity [12]. Meanwhile, mobile platforms like autonomous underwater vehicles (AUVs) are also overcoming geographical limitations—the WHOI's Sentry AUV mapped the 2020 Papua New Guinea landslide with 15 cm resolution, revealing the previously undetectable shear plane geometries [13].

Noticeably, Artificial Intelligence is also revolutionizing data interpretation across these systems. Specifically, machine learning algorithms can now achieve almost 94% accuracy in distinguishing earthquake signals from anthropogenic noise in OBS recordings [14], while transformer models applied to DAS data can predict slope instability precursors 2-3 hours before failure [15]. These

ISSN 2959-6157

advancements are being used by international collaborations. Japan's DONET system exemplifies it, combining 150 seafloor sensors with real-time AI processing to provide half-minute tsunami warnings [16]. Similarly, the European EMSO-ERIC network uses AUV fleets to adjust sensor placements based on seismic risk forecasts in a dynamic way—a strategy that reduced blind spots by a large amount.

Despite these achievements, several critical issues remain. For example, power constraints limit DAS sampling rates to <1 kHz in most deployments [17], potentially masking high-frequency precursors. Moreover, the lack of standardization between OBS manufacturers introduces issue of data compatibility [18]. Perhaps most consequentially, current systems exhibit severe geographic bias—over 70% of permanent seafloor sensors are concentrated in the North Pacific, leaving the Indian Ocean and South Atlantic not monitored [19]. Addressing these disparities will require not only technological innovation, but also certain funding models that incentivize data sharing across geopolitical boundaries.

3. Challenges and Future Perspectives in Seafloor Hazard Monitoring

Despite remarkable technological advancements, contemporary seafloor monitoring systems confront a series of challenges that undermine their efficacy. The extreme conditions of deep-sea environments, where pressures exceed 1,000 atmospheres and corrosive currents degrade materials, routinely compromise the sensor longevity; recent deployments in the Mariana Trench showed a 40% failure rate for standard OBS housings within 18 months [20]. Data transmission bottlenecks further worsen these hardware limitations. While modern fiber-optic cables theoretically enable real-time monitoring, latency issues plague actual systems: the Japan Trench DAS network experiences 8-to-15-second delays in tsunami detection due to signal processing overhead [21]. These problems are compounded by the lack of standardized protocols across monitoring platforms—a 2023 global audit identified 17 incompatible data formats among major OBS manufacturers, forcing researchers to discard 22% of potentially useful seismic records [22]. Most critically, the disconnect between data collection and emergency response persists; during the 2024 Solomon Islands earthquake, vital seafloor deformation metrics remained trapped in academic databases for 73 minutes while coastal communities awaited evacuation orders [23].

4. Conclusion

Therefore, submarine geohazards pose tremendous threats to both marine ecosystems and coastal societies, demanding continuous innovation in monitoring technologies. Our analysis demonstrates how OBS networks, DAS systems, and hydrophone arrays each contribute unique capabilities—from millimeter-scale strain detection to acoustic early warning—yet their individual limitations necessitate integrated solutions. The emergence of AI-enhanced multi-sensor platforms (e.g., the Neptune Canada network's 94% accuracy in landslide prediction) marks a shift toward holistic seafloor surveillance. However, enduring challenges, from hardware durability to institutional data silos, require coordinated action across both scientific, engineering, and policy efforts. Future progress hinges on three priorities: First, developing pressure-resistant sensors using graphene-ceramic composites, Moreover, establishing universal data standards through bodies like the Intergovernmental Oceanographic Commission, and implementing automated decision pipelines that convert real-time data into actionable alerts within 30 seconds. As climate change intensifies submarine landslide risks and deep-sea mining expands, these advancements will determine whether monitoring systems evolve from scientific tools into genuine lifesaving infrastructure.

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