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Hazard Zone Identification for Planned Submarine Gas Pipeline Routes in Pemping Island, Batam City, Riau Archipelago

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Abstract

To ensure the safe installation of underwater gas pipelines in Pemping Island, Batam City, Riau Islands, a comprehensive quantitative and qualitative study was conducted. This research identifies potential hazards along the pipeline route using pre-lay survey data from a multibeam echosounder (MBES) and side scan sonar (SSS). By analyzing this data in a Geographic Information System (GIS) the study identified four key hazards: extreme slopes, sediment types, sandwave areas, and submarine cable crossings. The results indicate that 30% of the total pipeline length traverses areas with extreme slopes (15 zones), 20% crosses areas with sediment-related hazards (12 zones), 11% passes through sandwave-prone areas (1 zone), and 2% has potential submarine cable crossings (1 zone). In total, approximately 48% (±574.13 meters) of the pipeline route intersects with combined hazards, distributed across 15 zones. These findings are critical for planning appropriate protection measures and mitigation strategies during pipeline installation. It is hoped that this research will assist pipeline installers in anticipating risks and minimizing potential losses.

Keywords: Hazards, Slope, Sediment Type, Submarine Gas Pipeline, Sandwaves, Submarine Cable

1. INTRODUCTION

There are many methods for distributing natural gas, one of which is through underwater gas pipelines. These pipelines play an important role in transporting natural gas from production sites to distribution networks or directly to the industrial consumers. Underwater pipelines are one of the most efficient distribution methods, as they minimize transportation costs and are often the preferred option for gas delivery [1]. Given their importance, proper pipeline construction planning is essential to ensure system safety.

[2] define a hazard as a condition, act, or the potential that could cause harm to human, property, processes, or the environment. For underwater pipelines, hazards encompass risks during the planning, installation, and post-installation phases. These hazards are categorized as internal or external. Internal hazards relate to design, material selection, and pipe thickness. Meanwhile external hazards arise from seabed environmental condition. Assessing seabed conditions is critical during the planning stage to mitigate damage risks. Key factors to consider including shipping traffic density, existing underwater structure, seabed surface conditions, sediment type, bathymetry, wind, currents, and wave height [3].

Several impacts from hazards frequently occur during underwater pipeline installation, including scouring, free spans, buckling, corrosion, obstructions, and depressions [3]. These potential hazards can be identified through a pre-lay survey conducted prior to pipe installation. The pre-lay survey serves to detect hazards that could endanger pipelines both during installation and subsequent operation [4]. Hydroacoustic instruments such as the multibeam echosounder (MBES) and side scan sonar (SSS) can be used to gather information about the position and extent of hazards along the planned pipeline route.

The MBES is an underwater mapping instrument that generates multiple measurement points covering the entire seabed. When these depth points are connected, they form a seabed profile used to analyze potential hazards for underwater pipeline planning [15]. SSS is a marine survey tool that uses acoustic technology to record underwater areas and generate images of various seabed objects [9]. These recordings are displayed as images, facilitating interpretation of seabed sediments and other features. Ultimately, the SSS image could enable the study potential marine hazards. Additionally, nautical charts play an important role in identifying

potential hazards along pipeline installation routes. These charts provide information about pre-existing submarine cable pathways, which informs both pipe installation planning and operational consideration.

Studies on pipeline route planning and hazards related to submarine pipeline routes have been widely conducted [7, 8, 9, 10, 11]. These studies examine all of the aspects in various ways: [7] and [8] carried out the submarine pipeline route planning and they used a number of different methods, such as Geographic Information Systems (GIS), dynamic programming, and logical reasoning frameworks. Impacts on submarine pipelines from ship anchor drops were studied by [10], and [8] assessed pipeline route hazards using SSS, seabed morphology from bathymetric measurements, and subsea seismic data. [11] reviewed various literature about the effects of submarine landslides on submarine pipeline routes (since 2008). Topics of [8] along with [10] are related closely within the current study. Although seismic data is not used in the present study, the similarity with [8] exists in the data's use for analysis. On the other hand, the reference [9] is similar in that the study occurs in the Riau Archipelago waters. Our study location is within the Riau Archipelago waters. This study therefore evaluates risks to submarine pipeline route planning since it lies within a zone showing great subsea activity. It uses bathymetric and SSS measurement data as inputs toward identifying potential hazards along the planned submarine pipeline route.

This study aims to identify potential hazards through pre-lay surveys for underwater pipeline installation near Pemping Island, Batam City. The identified hazard potentials include extreme slopes, sediment types, seabed morphology, and surrounding seabed objects. We hope that these findings could assist pipeline installers in hazard mitigation and loss prevention.

2. METODE

This study examines a section of the planned underwater pipeline in the waters off Pemping Island, Batam City, Riau Islands. The pipeline segment under examination spans approximately ±1.200 meters, covering a total area of about 60 hectares (Figure 1). Data specifications including type, format, and sources are presented in Table 1.

Table 1. Data Used in the Study

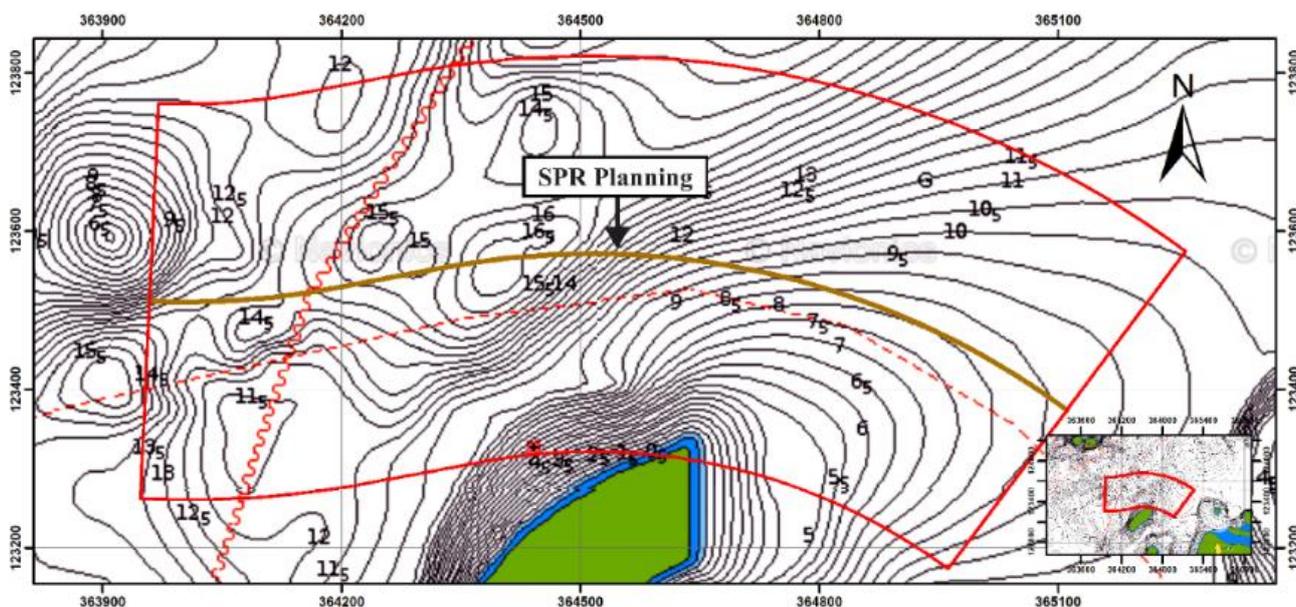| Data	Format	Sumber
x, y, z Multibeam Echosounder data	.XYZ	Pre-Lay Survey in Pemping island waters, 2024
Side Scan Sonar data	.logdoc	Pre-Lay Survey in Pemping island waters, 2024
Seabed natural gas pipeline route	.shp	Pre-Lay Survey in Pemping island waters, 2024
Nautical chart	.TIFF	SAS Planet

Figure 1. Study Site

The hazard identification process in this study generated both qualitative and quantitative data focusing on external hazards, including seabed morphology (particularly slope gradients), sediment types, and submerged objects (e.g., existing submarine cables) intersecting the planned pipeline route. Previous studies [3,12,13]

recommend avoiding pipeline installation in sea abbyses or extreme slopes to prevent potential post-installation landslides. Furthermore, seabeds composed of coarse sediments and rocks pose hazards due to their potential to create free spans. Ideal pipeline installation conditions require flat and stable seabed surfaces. MBES data were processed using GIS software to generate slope analyses, while SSS data were analyzed to characterize seabed composition. Nautical charts provided additional information for identifying pre-existing submarine cable locations.
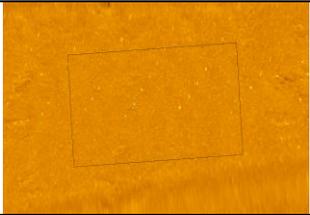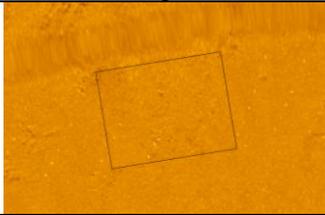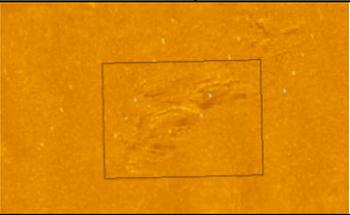
2.1. Hazard Identification

To identify the seabed slope characteristics, we utilized classification based on [14] as shown in Table 2. The slope classification is intended to identify the distribution, location, and the length of the underwater pipeline route which intersects with extreme slopes. In this study, we identified slopes under "moderately steep" and "steep" categories.

Table 2. Slope Classification

Slope angle (degrees)	Slope characteristics
0° - 2°	Flat
2° - 4°	Gentle
4° - 8°	Inclided/sloping
8° - 16°	Moderately steep
16° - 35°	Steep
35° - 55°	Very steep
>55°	Extremely steep/precipitous

The seabed sediment classification follows the methodologies of [3, 12, 13]. These studies identified sediment types hazardous to underwater pipeline, particularly rough-textured sediments containing rocks. The SSS images were interpreted along two recording lanes covering the overlapping pipeline route area. In this study, visual interpretation was conducted by analyzing shape, size, acoustic shadow, tone, texture, and patterns (Table 3).

Table 3. Sediment Types Based on Side Scan Sonar Images.

Interpreted parameters	Visual objects and sediment types		
	Soft	Rough	Rocky
Tone	Bright	Bright and medium	Dark
Size	Small and varied	Medium and varied	Varied
Shape	Tends to flatten following the contours of the seabed	Irregular	Shaped like a mound, elongated or irregularly rounded
Pattern	No structured distribution pattern	Dispersed and group	Individuals, groups, random like mounds
Shadow	Little or no shadow	Moderately shaded	Shaded
Texture	Soft and dense	Coarse and spotted	Uneven and irregular

The process of identifying fine sediment, coarse sediment, and rock types is referred to in studies by [15, 16, 17]. Based on SSS image interpretation, different sediment types exhibit distinct visual characteristics. Fine sediment typically appears in light tones with small, varied particle sizes, forming a relatively smooth surface that follows the seabed contour without a structured distribution pattern. It produces little to no shadow and has a fine, dense texture. In contrast, coarse sediment is characterized by light to moderate tones with medium-sized, varied particles, forming an irregular surface with random or clustered distribution patterns. It produces slight shadows and has a coarse, speckled texture. While the rocks generally display dark tones with large, varied sizes, forming irregular mound-like features with elongated or rounded shapes. They exhibit random individual or clustered distributions (e.g., mounds), produce distinct shadows, and have an uneven, irregular texture. This aligns with research by [18], which states that the general principle of SSS image interpretation
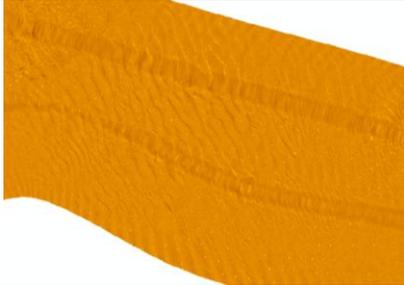
is that high backscatter indicates coarse sediment, while low backscatter indicates fine sediment. The sediment type interpretation is presented in Table 3.

Seabed stability serves as the primary factor ensuring pipeline operational safety, preventing pipeline suspension over unstable seabed surfaces. Sandwaves-affected areas pose significant risks as wave action can remove sediment support from operating pipelines [19]. Based on SSS image interpretation, sandwaves exhibit distinct visual characteristics. Sandwaves typically display a light tone, indicating that the seabed consists of fine sediment. Their wavy form with well-defined crests and troughs is a key identifying feature. Additionally, the crests of sandwaves produce shadow lines, providing information about their height and slope (Table 4). Our study only identifies occurrences of the sandwaves.

Table 4. Morphology of Sandwaves Based on Side Scan Sonar Images.

Interpreted parameters	Sandwaves visual
Tone	Bright
Size	Varied
Shape	Wavy
Pattern	Dispersed
Shadow	Shaded lines
Texture	Wavy

In this study, the determination of start and end points for potential hazards is based on visual interpretation of bathymetric and SSS survey results. These survey results meet International Hydrographic Organization (IHO) Order 1a standards for bathymetry, and the SSS image correction process follows the methodology described in [19]. The process for determining the start point, end point, and digitation for each hazard classification is illustrated in Figure 2a–2e. This methodology generates data on the distribution, position, and length of pipeline segments traversing hazardous areas. Figure 2a demonstrates the identification process for extreme slope hazards, Figure 2b for sediment type hazards, Figure 2c for sandwave risks, and Figure 2d for potential submarine cable crossings.

Each potential hazard was identified visually. For example, Figure 2a illustrates the sediment-based hazard identification process: first, sediment types were visually interpreted according to the classification in Table 3; then specific sediment-type areas along the proposed pipeline route were identified and delineated (with red circular boundaries); finally, the start/end points were determined, the pipeline route was digitized, and the distance of pipeline crossing the hazard zone was calculated. The same process was applied for other hazard identifications (Figures 2b–2d). As for, the distance calculation process differs slightly for overlapping hazards. Figure 2e demonstrates the start/end point determination and distance measurement for two or more overlapping hazards along the pipeline route. The start and end points were set at the outermost extremities of the overlapping hazard zones crossed by the pipeline route. After establishing these points, the section was digitized and its length calculated.

While the identification of sediment types and sandwaves from SSS data involves subjective visual interpretation, this same methodology has been employed in studies [19, 20, 21] for mapping seabed patterns and features. The determination of hazard starts, and end points was performed consistently according to the examples in Figures 2a–2e. This approach establishes standardized criteria based on three factors: distinctive geometric patterns, significant SSS anomalies, and spatially consistent features mapped using GIS tools. Although limited by its reliance on unvalidated survey interpretations, the method maintains objectivity through two measures: (1) application of numerical thresholds and (2) systematic cross-verification at each identified hazard point.
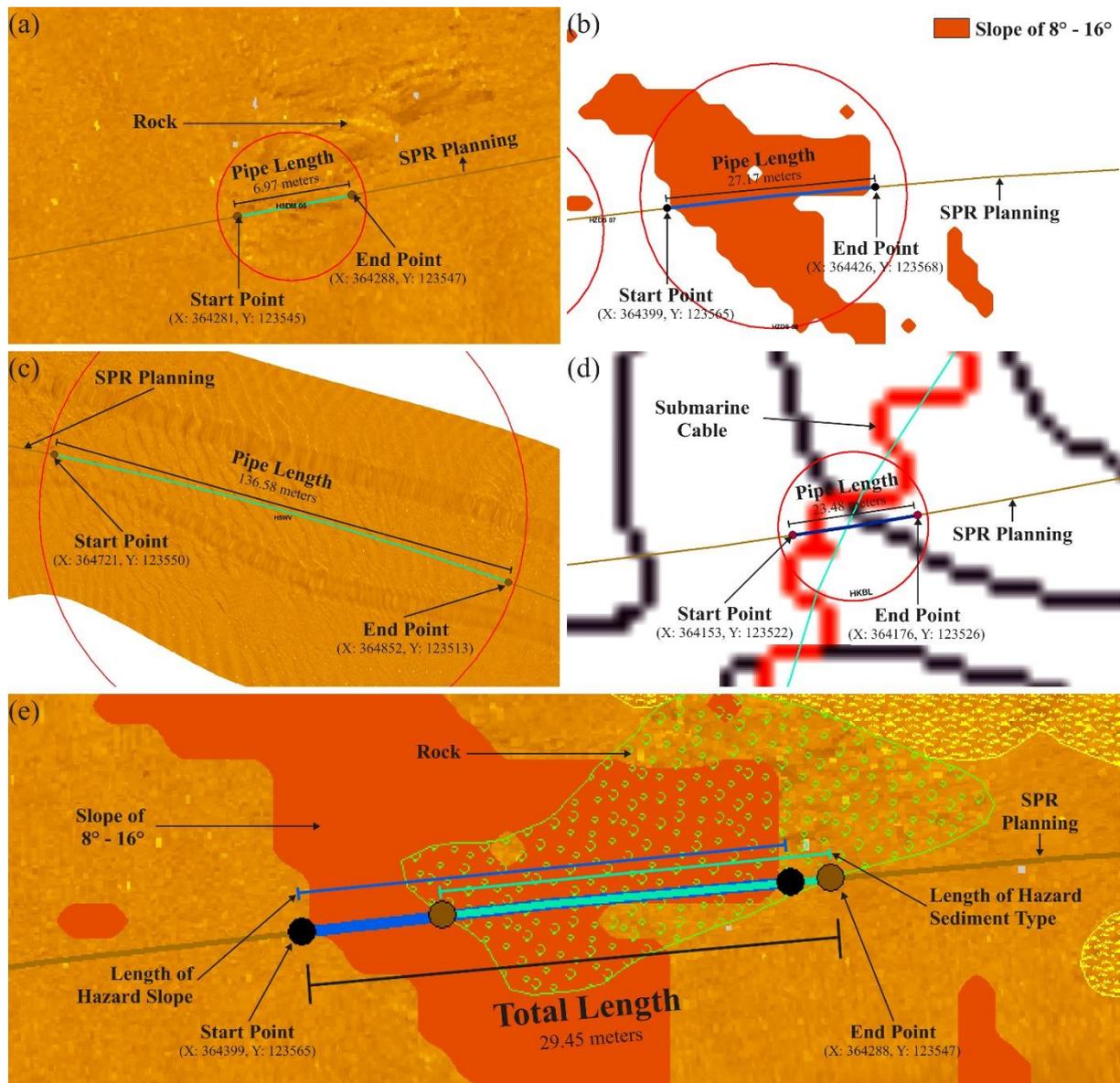
Figure 2. Example Showing The Position and Length of Pipeline Segments Traversing (a) Hazardous Sediment Types (b) Extreme Slopes (c) Sandwave Areas, (d) Submarine Cable Crossings, and (e) A Pipeline Segment Intersecting Two Combined Hazard Types.

3. RESULTS AND DISCUSSION

3.1. Distribution of Hazard Zones Traversed by The Pipeline route

The slope categories in our study area range from flat to steep, with no areas classified as "very steep" or "extremely steep" (Figure 3a). Figure 3b shows slopes categorized as "moderately steep" to "steep". We identified 13 hazardous zones along the pipeline route due to extreme slopes: 12 areas classified as "moderately steep" and 1 area classified as "steep". Figure 3c presents these hazard identification results.

The SSS image interpretation identified 12 areas with rough and rocky sediment types along the planned pipeline route (Figure 4). These hazardous zones, categorized by sediment type, are distributed across different slope classifications, with some areas overlapping (e.g., HZDS 06 and HSDM 9). SSS interpretation revealed only one sandwave-affected area intersecting the pipeline route (Figure 5). Furthermore, nautical chart analysis identified one submarine cable crossing (represented by red spiral lines in Figure 6), positioned such that it intersects with the planned natural gas pipeline.
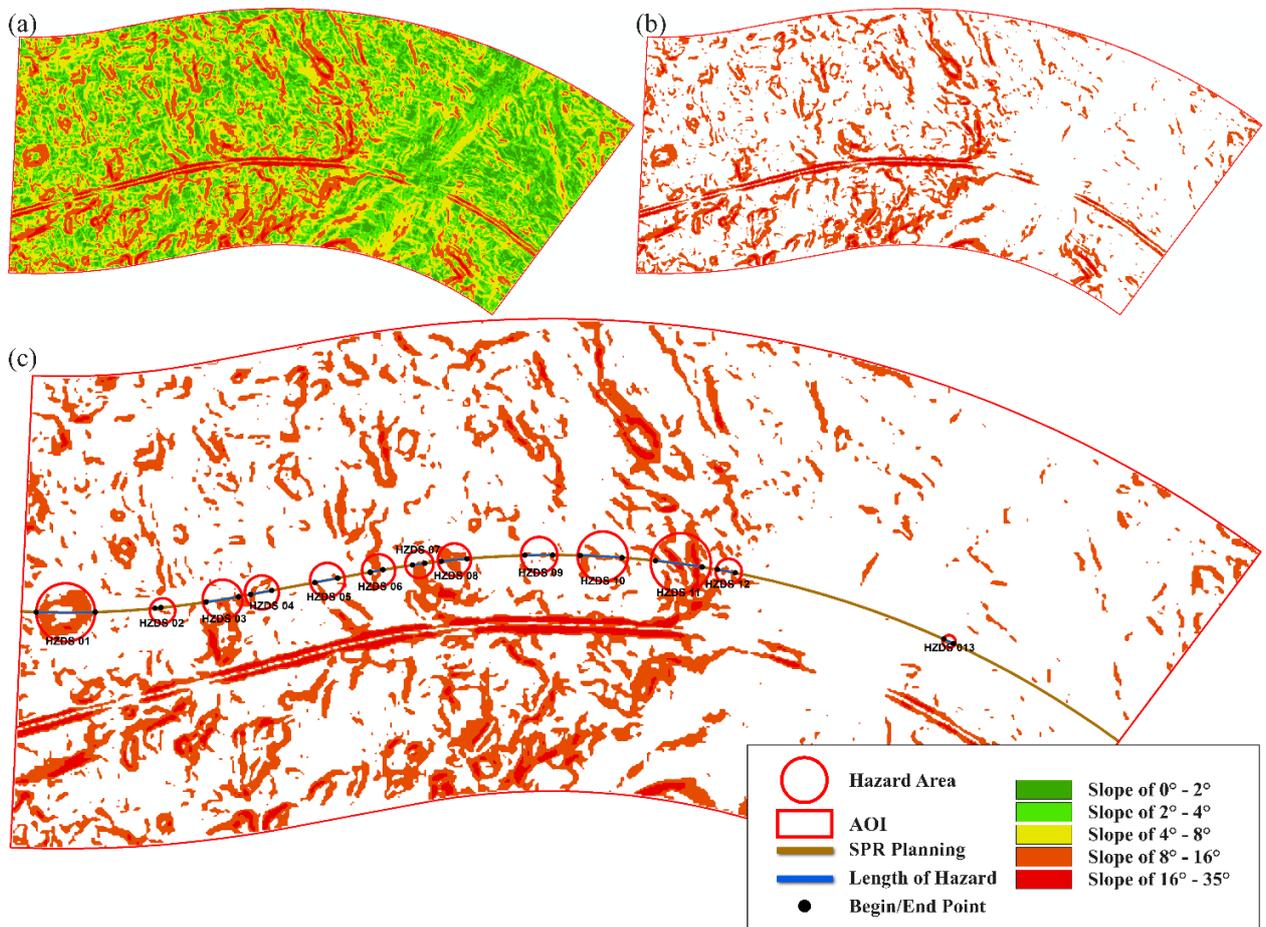
Figure 2. (a) Slope Classification Results, (b) Extreme Slope Category, and (c) Underwater Natural Gas Pipeline Traversing Extreme Slopes.
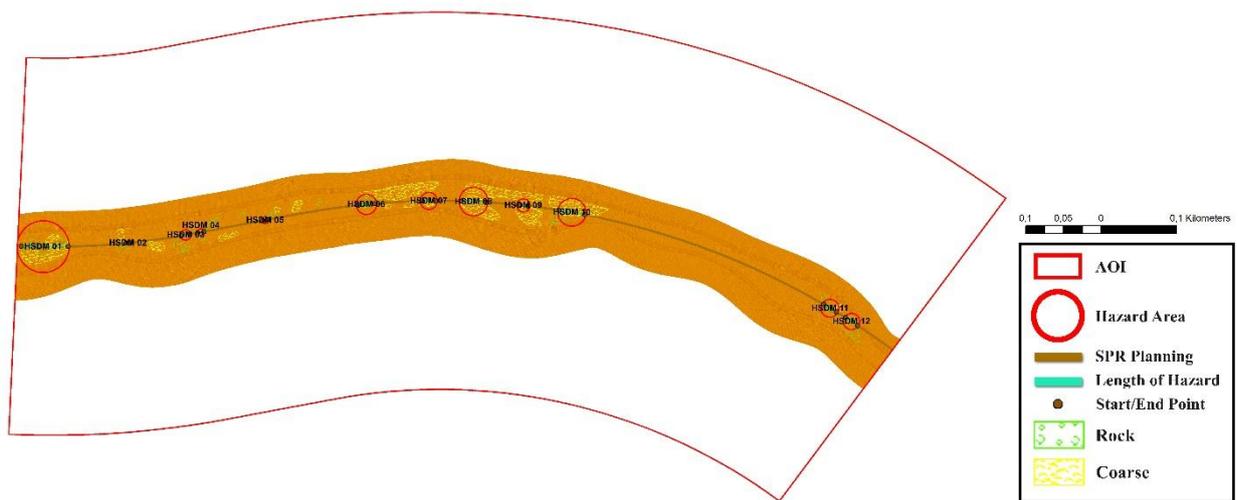
Figure 4. Pipeline Route Traversing The Hazardous Sediment.
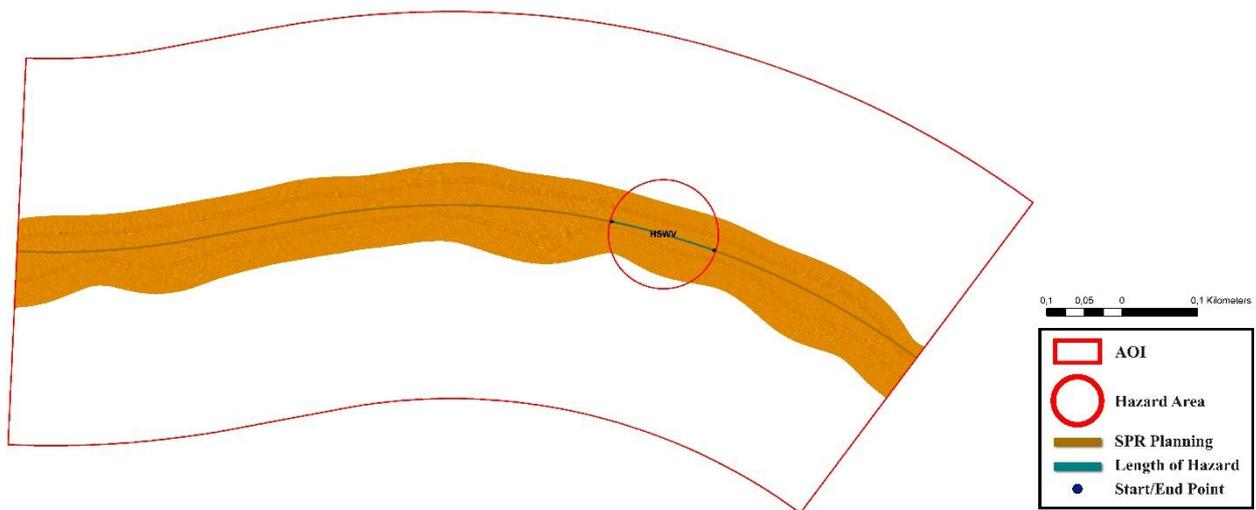
Figure 5. Pipeline Route Traversing Hazardous Sandwaves.
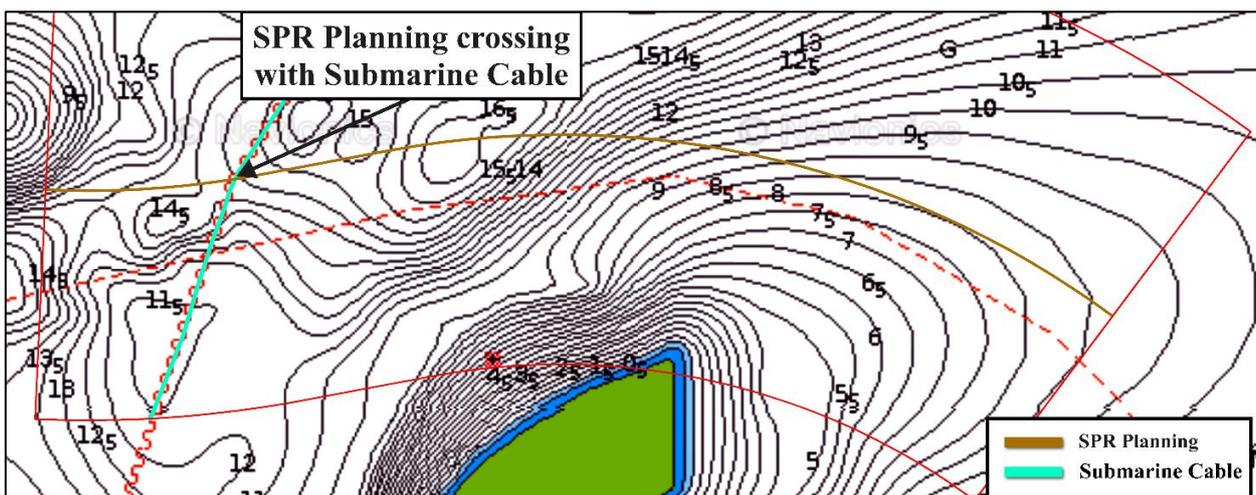
Figure 6. Pipeline route traversing submarine cable.

Figure 7 presents the integrated hazard assessment along the underwater pipeline route in the study area. The analysis identified 15 zones susceptible to combined hazard, including extreme slopes, problematic sediment types, sandwaves, and submarine cable crossings. These results provide critical information about: (1) hazardous pipeline segments, (2) affected pipe lengths, and (3) specific hazard types encountered.
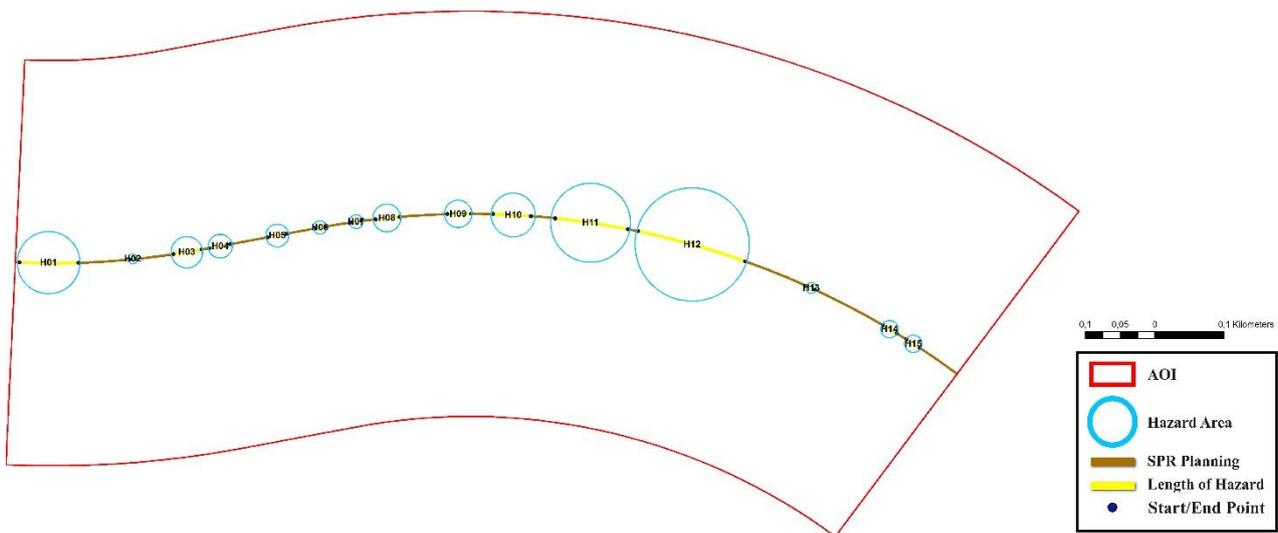
Figure 7. Underwater Pipeline Route that Traverses Various Combined-Hazard Areas.

3.2. Identification of Location and Length of Pipeline Route Traversing Hazardous Areas

Table 5 presents the start and end points, and lengths of pipeline segments traversing various hazard zones: extreme slopes, rough/rocky sediments, unstable seabed morphology (sandwaves), and submarine cable crossings. We assigned unique hazard identifiers (Hazard/HZD) based on emergence sequence, such as HZDS 01-HZDS 13 for extreme slope hazards, HSDM 01-HSDM 12 for hazardous sediment, HSWV for sandwave hazards, and HKBL for submarine cable crossings. The affected pipeline percentages were calculated relative to the total studied length (±1.200 m), which is, respectively, 30% for extreme slopes (356.83 m), 20% for hazardous sediment (252.88 m), 11% for sandwave hazards (136.58 m), and 2% for cable crossings (23.48 m).

Table 5 Location and Length of Pipeline Route Traversing Hazardous Areas

No.	Hazard ID	Start point		End point		Pipe length (m)
		X (m)	Y (m)	X (m)	Y (m)	
1	HZDS 01	363974	123511	364036	123511	61.82
2	HZDS 02	364098	123515	364105	123516	6.37
3	HZDS 03	364152	123522	364186	123527	34.81
4	HZDS 04	364199	123530	364221	123534	22.53
5	HZDS 05	364267	123542	364290	123547	24.22
6	HZDS 06	364325	123553	364338	123556	13.52
7	HZDS 07	364369	123561	364382	123563	12.94
8	HZDS 08	364399	123565	364426	123568	27.17
9	HZDS 09	364487	123571	364516	123571	29.16
10	HZDS 10	364545	123571	364589	123569	44.12
11	HZDS 11	364624	123565	364674	123559	49.72
12	HZDS 12	364689	123556	364708	123553	19.05
13	HZDS 13	364927	123482	364937	123478	11.40
14	HSDM 01	363963	123512	364025	123511	61.62
15	HSDM 02	364102	123515	364106	123516	4.75
16	HSDM 03	364174	123525	364185	123527	11.81
17	HSDM 04	364196	123529	364204	123531	8.34
18	HSDM 05	364281	123545	364288	123547	6.97
19	HSDM 06	364407	123566	364429	123568	21.63
20	HSDM 07	364491	123571	364509	123571	17.87
21	HSDM 08	364543	123571	364575	123570	32.26
22	HSDM 09	364619	123566	364631	123565	12.07
23	HSDM 10	364671	123559	364706	123553	34.86
24	HSDM 11	365020	123434	365037	123424	19.52
25	HSDM 12	365049	123417	365065	123406	19.36
26	HSWV	364721	123550	364852	123513	136.58
27	HKBL	364153	123522	364176	123526	23.48

3.3. Identification of Location and Length of Pipeline Route Traversing Combined Hazards

Table 6 presents the start and end points of pipeline segments affected by multiple combined hazards. Table 7 details the specific hazard combinations identified in each designated zone. We classified combined hazards using "H" prefixed with numerical identifiers. Analysis revealed that approximately 574.13 m (±) of the pipeline route, spanning 15 distinct zones, intersect with combined hazard areas. This represents roughly 47,84% (≈ 48%) of the total pipeline length under study.

The measured lengths of potential hazards (both individual and combined) intersecting the planned pipeline route were determined through the consistent identification method described in the methods section of this study. However, this approach has inherent limitations due to its subjective (interpretive). The technique was employed in this research to compensate for data limitations. For comparison, study [8] identified submarine pipeline hazards in the eastern Sardinia-Corsica region using bathymetric, SSS, and seismic data, where seismic data played a crucial analytical role. Similarly, study [9] utilized seismic data as a primary input for determining submarine pipeline routes. Consequently, the subjective technique for identifying start/end points in our study serves two important purposes: it addresses data constraints and represents a novel aspect that differentiates this research from previous studies.

Tabel 6. Location and Length, also the Combined Hazards Types Traversing through the pipeline Route.

No.	Hazard ID	Start Point		End Point		Pipe Length (m)	Combined Hazards Types
		X (m)	Y (m)	X (m)	Y (m)		
1	H01	363963	123512	364036	123511	73.32	■ (orange) ■ (yellow) ■ (gray)
2	H02	364098	123515	364106	123516	7.84	■ (orange) ■ (gray)
3	H03	364152	123522	364186	123527	34.81	■ (orange) ■ (gray) ■ (blue)
4	H04	364196	123529	364221	123534	25.87	■ (orange) ■ (yellow)
5	H05	364267	123542	364290	123547	24.22	■ (orange) ■ (gray)
6	H06	364325	123553	364338	123556	13.52	■ (orange)
7	H07	364369	123561	364382	123563	12.94	■ (orange)
8	H08	364399	123565	364429	123568	29.45	■ (orange) ■ (gray)
9	H09	364487	123571	364516	123571	29.16	■ (orange) ■ (yellow)
10	H10	364543	123571	364589	123569	46.12	■ (orange) ■ (yellow)
11	H11	364619	123566	364708	123553	90.02	■ (red) ■ (orange) ■ (yellow)
12	H12	364721	123550	364852	123513	136.58	■ (olive)
13	H13	364927	123482	364937	123478	11.40	■ (orange)
14	H14	365020	123434	365037	123424	19.52	■ (gray)
15	H15	365049	123417	365065	123406	19.36	■ (gray)
					Length Total:	574.13	

* The hazard types are color-coded: ■ Steep slope, ■ Moderate steep slope, ■ Rough sediment type, ■ Rocky sediment type, ■ Submarine cable, ■ Sandwaves.

3.4. Hazard Implication and Protection Methods of Submarine Pipeline Gas

The environmental factors, such as the seabed, including its morphology must be considered as primary factors in the submarine gas pipeline routes plan [12]. The consideration is crucial to avoid potential hazards such as free spins, scouring, and obstructions. A free span occurs when a submarine pipeline is suspended above the seabed with a gap beneath it [3]. This phenomenon can arise due to uneven seabed topography (as outlined in the DNV RP F-105 International Standard), changes in seabed caused by scouring, or pipeline routes intersecting with other submarine pipelines or cables [22]. Scouring poses a significant risk as sediment erosion. It can gradually erode the pipeline's outer coating, which leads to long-term damage. Meanwhile, obstruction is a rocky seabed condition, and it can force the pipeline to bend upward. The elevated spans occur in this condition, particularly in areas with bulge rock or large bedrocks along the route [3].

Our study identified 13 areas with extreme slopes, which heighten the risk of free spans and scouring, potentially damaging both the seabed and the pipeline's external coating [3]. Additionally, one area was found where the pipeline crosses a submarine cable, further increasing the likelihood of free spans. The presence of sandwaves in the seabed morphology suggests strong underwater currents [3], though current study has not yet been incorporated for validation. Such currents could accelerate scouring, destabilizing the pipeline and causing bending or displacement. Furthermore, 12 areas with coarse sediments and rocky seabed were identified as potential obstruction hazards.

Despite these risks, several protective measures can be implemented to safeguard the pipeline, including trenching, buckle arrestors [24], and concrete weight coating [25]. Trenching involves burying the pipeline in a dug-out seabed trench, shielding it from obstructions, scouring, and free spans. Buckle arrestors reinforce the pipeline by adding sections made of stronger materials, making it more resistant to bending (buckling). Concrete weight coating enhances the pipeline stability by adding a dense concrete layer (typically at least 1 inch thick [25]). The process can reduce risk of pipelines displacement, particularly occurs in unstable seabed areas like those with sandwaves. This research findings are intended to guide protective strategies for subsea pipeline installation, minimizing the impact of potential hazards.

4. CONCLUSION

This study examines seabed environmental factors (seabed morphology) to identify potential hazards from pre-lay survey data for subsea pipeline installation around Pemping Island, Batam City. The primary data used include MBES (bathymetric data) and SSS (seafloor imagery) measurements. The identified hazards include

extreme slopes, various sediment types, sandwaves, and objects located near the pipeline route. Hazard identification was conducted by interpreting MBES and SSS survey results, along with existing submarine cable data, all of which were categorized based on risk criteria for the planned pipeline. The lengths of pipeline segments exposed to individual and combined hazards were quantified using GIS software, yielding measurable risk exposure along the study area. The results indicate that the planned subsea gas pipeline route crosses 13 areas with extreme slopes, 12 regions with hazardous sediment types, 1 area with sandwaves, and 1 area intersecting an existing subsea cable. The percentages of total pipeline length affected by each hazard are: 30% for extreme slopes, 20% for sediment types, 11% for sandwaves, and 2% for cable crossings. Combined hazards affect approximately 574.13 meters of the pipeline (48% of the total surveyed length), distributed across 15 areas. Hopefully, this research will support pipeline installers in anticipating risks and minimizing potential losses.

REFERENCES

[1] F. P. Devi, "Implementasi Bayesian Network untuk perhitungan probabilitas pada penilaian risiko pipa bawah laut oleh faktor kapal," Tugas Akhir, Jurusan Matematika, Fakultas Matematika dan Ilmu Pengetahuan Alam, Institut Teknologi Sepuluh Nopember, Surabaya, 2017.

[2] S. Supriyadi dan F. Ramdan, "Identifikasi bahaya dan penilaian risiko pada divisi boiler menggunakan metode hazard identification risk assessment and risk control (HIRARC)," *Journal of Industrial Hygiene and Occupational Health*, vol. 1, no. 2, pp. 161–177, 2017, doi: 10.21111/jihoh.v1i2.892.

[3] B. Sadira, W. Windupranata, and S. Bachri, "Identifikasi dan klasifikasi variabel untuk desain lokasi dan rute pipa bawah laut," *ITB Indonesian Journal of Geospatial*, vol. 5, no. 1, pp. 52–69, 2016.

[4] H. J. Lekkerkerk, R. V. D. Velden, T. Haycock, P. Jansen, R. D. Vries, P. V. Waalwijk, and C. Beemster, *Handbook of Offshore Surveying Book One*. London, U.K.: Clarkson Research Service, 2006.

[5] C. A. Nugroho, H. M. Manik, D. A. Gultom, and M. Firdaus, "Implementasi Multibeam Echosounder untuk Pengukuran dan Analisis Data Kedalaman Perairan Teluk Jakarta Berdasarkan International Hydrographic Organization Standards," *POSITRON*, vol. 12, no. 1, pp. 60–71, 2022.

[6] C. H. Hobbs, D. B. Blanton, R. A. Gammisch, and J. Broadwater, "A marine archaeological reconnaissance using side-scan sonar, Jamestown Island, Virginia, USA," *Journal of Coastal Research*, vol. 10, no. 2, pp. 351–359, 1994.

[7] Y. Gao, H. Wang, B. Wang, L. Yang, and Z. Shi, "Submarine pipelines routing planning based on GIS and dynamic programming," in *Proc. 6th Int. Symp. Digital Earth: Models, Algorithms, and Virtual Reality*, vol. 7840, p. 78400P, 2009.

[8] S. Cecchini, D. Taliana, L. Giacomini, C. Herisson, and B. Bonnemaire, "Submarine geo-hazards on the eastern Sardinia-Corsica continental margin based on preliminary pipeline route investigation," *Mar. Geophys. Res.*, vol. 32, no. 1, pp. 71–81, 2011.

[9] W. C. Haneberg, "Stochastic incorporation of uncertainty and subjectivity in deepwater pipeline route optimization," in *Proc. Annu. Offshore Technol. Conf.*, vol. 2, pp. 1592–1603, 2015.

[10] Adnyani, L. P., Siregar, H. A., Putri, D. L., Nurmawati, N., & Wirawan, M. K. Analisis Risiko Kejatuhan Jangkar Terhadap Pipa Bawah Laut di Natuna. Zona Laut Jurnal Inovasi Sains Dan Teknologi Kelautan, 129-134. 2025.

[11] Fan, N., Jiang, J., Nian, T., Dong, Y., Guo, L., Fu, C.,Tian, Z. & Guo, X. Impact action of submarine slides on pipelines: A review of the state-of-the-art since 2008. Ocean Engineering, 286, 115532. 2023.

[12] A. C. Palmer and R. A. King, *Subsea Pipeline Engineering*. Tulsa, OK: Penwell Corporation, 2004.

[13] S. Sulardi, "Konstruksi instalasi pipa migas bawah laut di Teluk Balikpapan," *Jurnal Info Teknik*, vol. 22, no. 2, pp. 1-14, 2020.

[14] R. A. Zuidam, *Aereal Photo-Interpretation in Terrain Analysis and Geomorphologic Mapping*. Netherlands, 1985.

[15] S. Mandasari and Y. Yuwono, "Studi Kelayakan Lokasi Rencana Peletakan Jack-Up Drilling Rig Menggunakan Hasil Pencitraan Side Scan Sonar," *Geoid*, vol. 8, no. 2, pp. 144–150, 2013.

[16] F. Busro, Khomsin, and D. G. Pratomo, "Identifikasi Objek Dasar Laut Dari Data Side Scan Sonar (Studi Kasus: Perairan Pelabuhan Pt. Petrokimia Gresik) / Identification of Seabed Objects from Side Scan Sonar Data (Case Study: Port Waters of Pt. Petrokimia Gresik)," *Geoid J. Geod. Geomat.*, vol. 19, no. 1, pp. 88-95, Agst. 2023.

[17] R. Nurkhayati dan H. M. Manik, "GIS Untuk Integrasi Interpretasi Substrat Dasar Perairan menggunakan Pengolahan Citra ALOS-AVNIR dan Side Scan Sonar," *J. Oto. Ktrl. Inst. (J. Auto. Ctrl. Inst.)*, vol. 1, no. 1, pp. 25-39, 2016.

[18] S. P. Sari, *Deteksi dan interpretasi target di dasar laut menggunakan instrumen side scan sonar*, Skripsi, Institut Pertanian Bogor, 2009.

[19] E. Prayetno and H. Ulinnuha, "Pemanfaatan citra Side Scan Sonar untuk identifikasi objek bawah laut," *Journal of Geospatial Information Science and Engineering*, vol. 3, no. 1, pp. 49–60, 2020.

[20] M. Z. Lubis and W. Anurogo, "Identifikasi profil dasar laut menggunakan instrumen side scan sonar dengan metode beam pattern discrete-equi-spaced unshaded line array," *Jurnal Kelautan*, vol. 10, no. 1, pp. 1–10, 2017.

[21] R. A. Farihah, H. M. Manik, and G. Harsono, "Pengukuran dan analisis hambur balik akustik menggunakan teknologi multibeam echosounder untuk klasifikasi sedimen dasar laut Teluk Palu," *J. Ilmu Teknol. Kelautan Tropis*, vol. 12, no. 2, pp. 437–453, 2020.

[22] M. B. Ravenska and N. M. R. R. C. Perbani, "Identifikasi hazard dari hasil data free span pada jalur pipa bawah laut Lapangan Bekapai menggunakan data multibeam echosounder dan side scan sonar," *Reka Geomatika*, vol. 1, no. 1, pp. 50–61, 2018.

[23] A. N. Hertia, "Studi estimasi scouring dan free spans (bentangan bebas) pada pipa bawah laut PT ExxonMobil di perairan Tuban, Jawa Timur," Tugas Akhir, Institut Teknologi Sepuluh Nopember, Surabaya, 2003.

[24] A. H. Mousselli, *Offshore Pipeline Design, Analysis, and Methods*. Tulsa, OK: Penwell Publishing Company, 1981.

[25] J. Lee, *Introduction to Offshore Pipelines and Risers*. Houston, TX: JYL Pipeline Consultant, 2007.