Route Selection and Environmental Strategies in Subsea Pipeline Engineering

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Why Subsea Pipeline Installation Is Not Merely a Construction Issue: A Conceptual Perspective from the Pemping Island Study

Abstract

Subsea pipeline installation is a critical component of offshore energy infrastructure that has traditionally been understood as a technical construction activity on the seabed. However, developments in the literature indicate that the success of this system is not solely determined by the installation phase, but is highly dependent on early planning processes, particularly pipeline route selection and seabed condition assessment. This article aims to conceptually examine that subsea pipeline installation is a multidimensional process involving technical, spatial, and risk-based aspects. The study is conducted using a literature review approach, referring to studies on Pemping Island as well as subsea pipeline engineering literature. The results show that seabed conditions such as slope, sediment type, and geohazard zones have a significant influence on pipeline route stability. Therefore, subsea pipeline installation should be understood as part of a risk-based decision-making system, rather than merely a construction activity.

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1. Introduction

Subsea pipelines are vital infrastructure for transporting energy from offshore areas to onshore facilities. However, in engineering practice, their installation is often perceived merely as a construction activity focused on physical placement on the seabed, with success measured by installation methods, equipment performance, and execution efficiency. This perspective, however, does not fully capture the underlying complexity, as project success is highly influenced by the planning stage, particularly in determining the optimal pipeline route. Poorly designed routes can lead to various risks, including instability due to unfavorable geotechnical conditions, damage caused by human activities such as shipping and fishing, and environmental impacts from ocean currents, waves, and seabed morphology [1]. Subsea pipeline planning therefore requires a more comprehensive approach than simply construction analysis and route length optimization. A spatial analysis–based approach enables the integration of environmental protection, cost, and safety aspects into a "cost surface," which can then be processed using methods such as least-cost path or dynamic programming to produce routes that are more economical, safer, and easier to construct [2]. Nevertheless, the literature also emphasizes that the complexity of subsea pipeline systems does not end with geometric route selection. The interaction between the pipeline and the seabed, as well as on-bottom stability, are critical to long-term safety and reliability. Modern design integrates route selection with on-bottom stability criteria and pipe soil interaction directly into the objective function, allowing optimal routes to simultaneously minimize mitigation requirements (e.g., ballast, additional protection) and operational costs [3].

The case study of Pemping Island can be positioned in line with international research highlighting that seabed geospatial and environmental characteristics are inseparable from pipeline route design. Hazard zones such as steep slopes, soft sediments, and sandwaves represent specific forms of seabed geohazards that must be incorporated early in the route planning process. Various studies show that pipeline or cable routes crossing steep and unstable slopes increase the risk of submarine landslides, liquefaction, and pipeline deformation. Therefore, route selection should identify and classify high-slope areas as “dangerous zones” within GIS-based least-cost path analysis [4]. Other studies have found that sloping seabeds also influence buckling behavior and lateral stability of high-pressure/high-temperature (HP/HT) pipelines, indicating that slope effects cannot be neglected in design [5].

For soft sediments, several studies indicate that the combination of waves, currents, and loose soils (such as unconsolidated clay) accelerates erosion and local scour processes, which can lead to free spans and even pipeline suspension, particularly in areas with complex topography and shallow waters [6]. Similar conditions have been examined on sandy slopes and inclined seabeds, where pore pressure response and liquefaction potential around buried pipelines vary significantly depending on soil properties and burial depth [7].

Based on these considerations, this article re-examines subsea pipeline installation as a process that is not merely a construction activity, but also an integral part of a risk-based decision-making system.

2. Materials and Methods

This study employs a qualitative approach using a conceptual literature review method. This approach is selected because the research focuses on examining theories, concepts, and scientific findings relevant to subsea pipeline route determination, particularly in the Pemping Island area. The primary data sources are obtained from various scientific literature, including reputable international journals, conference proceedings, industry technical standards, and reference books related to subsea pipeline engineering. The data collection process is carried out through the identification, selection, and evaluation of literature that is directly related to the research topic. The selected literature focuses on studies of hazard zones, seabed characteristics, as well as environmental and technical factors influencing pipeline route planning. In addition, this research also refers to commonly used international guidelines and standards in the oil and gas industry to ensure the validity and relevance of the analysis.

The analysis stage is conducted using a conceptual synthesis method, which integrates various concepts and findings from the reviewed literature. The main focus of the analysis includes three key aspects: route selection, seabed interaction, and risk-based design. In the route selection stage, the study examines determining factors in selecting optimal pipeline routes, such as geological conditions, seabed topography, and potential environmental risks. In the seabed interaction aspect, the relationship between pipeline structures and seabed conditions is analyzed, including pipeline stability, potential displacement, and the influence of ocean currents and sediments. Meanwhile, in risk-based design, the study emphasizes the identification, evaluation, and mitigation of risks that may occur during both the installation and operational phases of the pipeline.

Through this approach, the study aims to develop a more comprehensive and integrated understanding of subsea pipeline installation from a theoretical perspective. The results of the synthesis are expected to provide a strong conceptual foundation to support decision-making in planning pipeline routes that are safe, efficient, and sustainable, particularly in study areas with complex environmental conditions such as Pemping Island.

3. Results

3.1 Route Selection as an Initial Risk Determinant

Route selection is widely regarded as the most critical stage in the design cycle of subsea pipelines, particularly in the context of developing a gas pipeline system from Natuna to Pulau Pemping. Early routing decisions will effectively determine the geological, geotechnical, and environmental conditions that the pipeline will encounter throughout its service life. Several studies emphasize that route optimization at this initial stage is crucial to ensure the safety and serviceability of offshore gas transmission systems. Given that complete avoidance of geohazards along this corridor is not always possible, selecting an optimal route becomes the primary strategy to minimize potential environmental and economic consequences resulting from pipeline failure [1]. Furthermore, in the case of this pipeline development, errors or oversimplifications during the route selection stage would be difficult to correct during construction. Once installed on the seabed, the pipeline position becomes essentially permanent. Any additional mitigation measures such as protective structures, burial, ballast installation, or configuration adjustments would only partially reduce the risks and would require significant additional costs. Therefore, careful and comprehensive route selection is essential to ensure the long term reliability and efficiency of the gas pipeline system connecting Natuna and Pulau Pemping [8].

3.2 Pipeline Seabed Interaction (Seabed Interaction)

The interaction between the pipeline and the seabed is a complex phenomenon involving both soil mechanics and the structural response of the pipeline. In the context of gas pipeline development from Natuna to Pulau Pemping, this interaction becomes particularly critical due to varying seabed conditions along the route. After installation, the pipeline does not remain in a static condition but undergoes continuous interaction with its surrounding environment.

Several key mechanisms influence this interaction, including sediment deformation due to pipeline weight, changes in soil resistance, hydrodynamic effects such as ocean currents, and free spanning caused by local scour. These conditions may lead to lateral displacement, settlement, and excessive structural stress in the pipeline. This indicates that pipeline stability is not solely determined by material strength, but is also highly dependent on the geotechnical characteristics of the seabed. In other words, the pipeline and the surrounding soil form an integrated system that cannot be analyzed separately [9].

3.3 Spatial Distribution of Geohazards

Seabed conditions exhibit significant spatial variability. In the context of Pulau Pemping, hazard zones are not evenly distributed but instead form distinct patterns based on geospatial parameters. The main parameters identified include seabed slope, sediment type and consistency, as well as the presence of sandwaves and other dynamic morphological features. Study results indicate that the combination of these parameters produces varying levels of risk along the pipeline route. This means that within a single pipeline alignment, multiple segments may exist with contrasting risk characteristics. These findings highlight that design approaches cannot be uniform, but must instead be adaptive to local conditions [10]. Various studies employ GIS, multibeam bathymetry, 3D seismic data, and AUV data to map seabed features such as steep slopes, valleys, canyons, and sandwaves, as well as hazardous features including landslides, pockmarks, faults, and shallow gas accumulations. These datasets are then used to classify areas into low and high vulnerability zones [11]. GIS-based tools further integrate least-cost path analysis with geohazard criteria such as steep slopes, fault zones, and landslide-prone areas to determine pipeline or cable routes that minimize crossings through hazardous regions while remaining economically viable. In practical design, this spatial mapping serves as an initial step for corridor selection, prior to more detailed analyses of pipeline soil interaction and structural response [12].

3.4 Risk-Based Design Approach in Subsea Pipelines

The complexity of seabed conditions necessitates the use of a risk-based design approach in subsea pipeline planning, particularly for gas pipeline development from Natuna to Pulau Pemping.

This approach focuses on the identification, evaluation, and mitigation of risks from the earliest design stages, where various studies define pipeline risk as a function of failure probability and its consequences, such as leakage, rupture, impact damage, and long-term corrosion [13]. Environmental and geotechnical factors including seabed topography, sediment movement, current and wave forces, soil properties, and pipeline soil interaction are incorporated into risk models to assess the need for burial, trench depth, and protection against dropped objects [14]. Within this framework, risk is understood as a function of the probability of failure and the resulting consequences. This approach enables engineers to prioritize high-risk areas, optimize pipeline routing based on safety levels, and reduce the need for costly technical interventions during the construction stage. A risk-based design must integrate geospatial, geotechnical, and operational data simultaneously to produce more robust and efficient decision-making, ensuring the long-term reliability and safety of the subsea pipeline system along the Natuna to Pemping corridor [15].

4. Discussion

The findings of this study indicate that subsea pipeline installation cannot be understood merely as a technical construction process carried out in the field. Based on subsea pipeline literature, it is evident that the most critical decisions occur at the early design stage, particularly during route selection. At this stage, the pipeline alignment effectively “locks in” a significant portion of the system’s risk, meaning that even small errors in route determination can lead to major and permanent consequences [9].

In practice, approaches that overly emphasize construction tend to assume that all problems can be resolved during installation. However, the findings suggest that many issues are already embedded before the pipeline is installed, primarily due to complex seabed conditions. In other words, construction mainly serves as the execution phase of prior decisions, rather than the stage that determines system safety. The concept of seabed interaction further clarifies this point. Subsea pipelines do not exist in a fully stable or isolated condition, but continuously interact with the surrounding seabed. These interactions may result in responses such as settlement, lateral displacement, and free spanning due to sediment changes [9]. This implies that the pipeline system is inherently dynamic, rather than static as often assumed in simplified approaches.

On the other hand, the case of Pulau Pemping demonstrates that seabed characteristics are highly heterogeneous. There are areas with steep slopes, soft sediments, and zones with active sandwaves [10]. This is significant because it shows that risk is not evenly distributed, but varies spatially depending on location. Consequently, design approaches that assume uniform conditions along the entire route become less relevant in real-world scenarios. This highlights that the core issue lies not only in technical installation aspects, but also in how subsea space is understood and interpreted. A risk-based design approach is therefore essential, as risk cannot be separated from environmental conditions and early design decisions. In this context, pipeline routing should not aim solely for the shortest or cheapest path, but rather for the safest route based on spatial risk distribution [15].

In conclusion, subsea pipeline installation should no longer be viewed merely as a construction activity. A more appropriate perspective is to consider it as a risk-based decision-making process that begins with seabed condition mapping and continues through to field implementation. Construction thus represents only the final stage of a system that has already been largely determined from the outset through design and spatial analysis.

5. Conclusions

This study concludes that subsea pipeline installation should not be interpreted solely as a technical construction activity, but rather as an integrated, risk based decision making process that begins at the early design stage. The findings highlight that route selection plays a decisive role in determining the overall risk profile of the system, as it effectively locks the pipeline into specific geological, geotechnical, and environmental conditions throughout its service life. Consequently, errors at this stage are difficult to correct and may lead to long term technical and economic consequences.

Furthermore, the interaction between the pipeline and the seabed demonstrates that pipeline systems are inherently dynamic. Stability is not only governed by material strength, but also by complex soil structure interactions and environmental forces. This reinforces the need to consider seabed characteristics as an integral component of pipeline design rather than a secondary factor addressed during construction.

The case of Pulau Pemping also confirms that seabed conditions exhibit significant spatial variability, resulting in uneven risk distribution along the pipeline route. Therefore, uniform design approaches are insufficient, and adaptive, spatially informed strategies are required. The application of GIS based analysis and geohazard mapping provides an effective foundation for identifying high risk zones and optimizing pipeline routing.

Overall, a risk based design approach that integrates geospatial, geotechnical, and operational data is essential to achieve safe, efficient, and sustainable subsea pipeline systems. In this context, construction should be understood as the final implementation phase of decisions that have been fundamentally shaped during the planning and design stages.

References

[1] N. Makrakis, P. Psarropoulos, D. Chatzidakis, and Y. Tsompanakis, "Optimal Route Selection of Offshore Pipelines Subjected to Submarine Landslides," *Open Civ. Eng. J.*, 2022, doi: 10.2174/18741495-v16-e220922-2022-30.

[2] N. Makrakis, P. Psarropoulos, and Y. Tsompanakis, "GIS-Based Optimal Route Selection of Submarine Cables Considering Potential Seismic Fault Zones," *Appl. Sci.*, 2023, doi: 10.3390/app13052995.

[3] K. Hafez, M. Abdelsalam, and A. Abdelhameed, "Dynamic on-bottom stability analysis of subsea pipelines using finite element model-based general offshore analysis software: a case study," *Beni-Suef Univ. J. Basic Appl. Sci.*, vol. 11, 2022, doi: 10.1186/s43088-022-00219-x.

[4] D. M. Rocha *et al.*, "Optimization of Submarine Pipeline Routes Considering Slope Stability," 2015, doi: 10.4043/25711-ms.

[5] I. Seyfipour, R. Mirghaderi, and M. Bahaari, "Buckling and stability of subsea HP/HT pipelines on laterally sloping seabeds," *J. Ocean Eng. Mar. Energy*, vol. 9, pp. 1–23, 2022, doi: 10.1007/s40722-022-00245-y.

[6] P. Huang, X. Meng, H. Dong, and L. Chong, "Numerical Modeling of Submarine Pipeline Scouring under Tropical Storms," *Water*, vol. 13, p. 1425, 2021, doi: 10.3390/w13101425.

[7] J. Lin, Y. Gao, Y. Guo, J. Liu, and L. Feng, "Wave-induced sloping seabed residual response around a buried pipeline," *Mar. Georesources Geotechnol.*, vol. 43, pp. 1355–1373, 2024, doi: 10.1080/1064119x.2024.2407844.

[8] G. I. G. Imanova and E. M. E. Mammadli, "LAYING OF PIPELINES IN SUBSEA TAKING INTO ACCOUNT THE PROTECTION OF THE ENVIRONMENT," *PAHTEI-Procedings Azerbaijan High Tech. Educ. Institutions*, 2022, doi: 10.36962/pahtei15042022-23.

[9] N. Makrakis, P. N. Psarropoulos, and Y. Tsompanakis, "applied sciences GIS-Based Optimal Route Selection of Submarine Cables Considering Potential Seismic Fault Zones," 2023.

[10] P. Island, B. City, and R. Archipelago, "Zona laut," vol. 6, no. 2, pp. 182–192, 2025.

[11] I. H. Hariyanto, Khomsin, N. D. Adhi, A. Rachmat, and K. R. Noer, "Utilization of Bathymetry Data and Backscatter in Geohazard Identification Process at Drilling Stage," in *BIO Web of*

Conferences, 2025. doi: 10.1051/bioconf/202515707003.

[12] J. Nicholls, "SS:Geohazard Risk Assessment-Pipeline integrity in geohazard prone seabed terrain - what is the real risk?," 2009, doi: 10.4043/20206-ms.

[13] F. Jiang and S. Dong, "Risk-based integrity model for offshore pipelines subjected to impact loads from falling objects," *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.*, vol. 235, pp. 623–641, 2020, doi: 10.1177/1475090220960562.

[14] G. Ismayilov, M. Shahlarli, and H. Ismayilova, "Integrated Fuzzy AHP and SAM Decision Framework for Offshore Pipeline Risk Management," *Int. J. Sustain. Risk Control*, 2025, doi: 10.64599/eiar6923.

[15] D. J. White and D. N. Cathie, *Geotechnics for subsea pipelines*. 2011.