

Subsea Pipeline Route Selection Based on Sediment Geotechnics and Hydrodynamics: A Systematic Review

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ABSTRACT

Subsea pipeline route selection is a critical stage because corridor decisions determine geotechnical, hydrodynamic, construction, and operational risks. This systematic review aims to synthesize research developments on the integration of seabed sediment characteristics and hydrodynamic factors for pipeline route selection in shallow waters. A Systematic Literature Review (SLR) method was structured following PRISMA 2020 through the stages of identification, screening, eligibility assessment, and inclusion. The search was designed on Scopus, ScienceDirect, SpringerLink, Google Scholar, and Dimensions using combinations of keywords: submarine pipeline, route selection, geotechnical, hydrodynamic, pipe-soil interaction, on-bottom stability, soft clay, and multi-criteria decision analysis. Thematic synthesis indicates that undrained shear strength, embedment, bearing capacity, wave-current, and scour are the main parameters that interact in determining stability. Recent literature also shows a shift toward numerical modeling and site-based evaluation; however, studies integrating the spatial variability of geotechnics and hydrodynamic loads within a single route selection matrix remain limited. Therefore, an integrated multi-criteria evaluation framework is needed to compare route alternatives in a measurable manner in shallow tropical coastal waters.

Keywords: submarine pipeline, route selection, geotechnics, hydrodynamics, SLR

INTRODUCTION

Subsea pipelines are strategic infrastructure for connecting energy production, processing, and distribution facilities. At the planning stage, route corridor selection has direct consequences for pipeline protection requirements, installation methods, construction costs, structural integrity, and operational risks. Therefore, route decisions cannot be based solely on the shortest distance but must consider seabed conditions, environmental loads, geohazards, existing infrastructure, and pipe-soil response [1]–[3].

In shallow coastal waters, the main challenge lies in the interaction between relatively soft sediments and wave and current forces that remain significant close to the seabed. Under saturated clay conditions, undrained shear strength (S_u), soil sensitivity, stress history, and embedment depth control the vertical bearing capacity and lateral resistance of the pipeline [4]–[7]. At the same time, hydrodynamic loads are influenced by wave height and period, current velocity, direction of approach, water depth, and non-dimensional parameters such as the Keulegan-Carpenter number [8]–[10].

The DNV-RP-F109 and DNV-RP-F114 guidelines provide a technical framework for on-bottom stability and pipe-soil interaction; however, these standards still

require representative site data and engineering judgement in determining input parameters [11], [12]. Recent studies show that site-based evaluation, CFD/FEM modeling, and large-deformation analysis are increasingly used to capture pipe-soil response and scour more realistically [13]–[17].

On the route selection side, Multi-Criteria Decision Analysis (MCDA) and the Analytic Hierarchy Process (AHP) can unify criteria with different units into comparative scores. These approaches have been applied to subsea pipeline routing and demonstrate benefits in decision-making transparency [18]–[20]. However, some routing studies still treat geotechnical, hydrodynamic, geohazard, and constructability parameters as independent criteria, while the physical relationships among parameters—for example, the influence of S_u and embedment on resistance under wave-current loading—are not always explicitly represented.

The research proposal underlying this article positions its contribution in developing an integrated multi-criteria evaluation framework to compare three candidate routes in the Balongan corridor. This framework combines spatial geotechnical characterization, hydrodynamic modeling, lateral-vertical stability evaluation, and MCDA/AHP into a

single analytical chain. This position is consistent with the aim of the research proposal: to produce a technical feasibility ranking among routes and to test the reliability of the framework, rather than merely selecting a single route in an ad-hoc manner.

Based on this background, this systematic review aims to: (1) identify the geotechnical parameters most relevant to pipeline stability; (2) evaluate wave-current modeling approaches in shallow waters; (3) synthesize the development of pipe-soil interaction, embedment, scour, and on-bottom stability models; and (4) assess how MCDA/AHP can integrate these factors for subsea pipeline route selection.

RESEARCH METHODS

This study employs a descriptive Systematic Literature Review (SLR) following the PRISMA 2020 reporting guidelines [21]. PRISMA is used as a transparency framework to document information sources, search strategies, eligibility criteria, selection processes, and synthesis. Since PRISMA was originally developed primarily for systematic reviews in the health field, its application to the engineering topic in this article serves as a replicable reporting and search framework, rather than as a mandatory statistical meta-analysis.

The review questions are formulated as follows: which geotechnical and hydrodynamic parameters most influence route feasibility; how are pipe-soil interaction and on-bottom stability modeled; and how can these parameters be integrated into multi-criteria route selection. The search was designed on Scopus, ScienceDirect, SpringerLink, Google Scholar, and Dimensions. The priority publication range was set to 2020–2026 to capture recent literature, while pre-2020 publications were selectively retained only when they

constitute foundational sources, classical models, or standards that remain direct references.

The main search string combines the terms: ("submarine pipeline" OR "subsea pipeline") AND ("route selection" OR routing OR alignment) AND (geotechnical OR sediment OR "soft clay" OR "pipe-soil interaction") AND (hydrodynamic OR wave OR current OR scour OR "on-bottom stability"). Additional searches used ("multi-criteria" OR AHP OR MCDA) as well as Indonesian or tropical shallow water regional terms. All results were exported to a reference manager for deduplication and source recording.

Inclusion criteria cover journal articles or scientific proceedings that address at least one core component—routing, seabed geotechnics, hydrodynamics, pipe-soil interaction, scour, pipeline stability, or MCDA—with a relationship that can be drawn to route selection decisions. Industry standard documents are included as normative sources. Articles without full text, those irrelevant to subsea pipelines, or those addressing only internal pipeline operations without any link to the seabed environment are excluded.

Data were extracted into a synthesis matrix containing author/year, location or environmental context, sediment type, geotechnical parameters, hydrodynamic parameters, analysis approach, stability/routing variables, and main findings. This structure replaces the 'governance innovation' variable, which is not relevant to the engineering topic. Analysis was conducted through simple descriptive statistics and thematic synthesis. The four main themes established are: geotechnical characterization; hydrodynamics and scour; pipe-soil interaction/on-bottom stability; and route selection/MCDA.

Table 1. Search strategy and data extraction focus

Component	Example Search Terms	Data Extracted
Routing	route selection, routing, alignment	route alternatives, length, obstacles, constructability
Geotechnics	soft clay, S_u , CPT, sediment, bearing capacity	S_u , OCR, sensitivity, embedment, bearing capacity
Hydrodynamics	wave, current, Morison, KC, scour	H_s , T_p , current, drag/lift/inertia, scour
Stability	pipe-soil interaction, on-bottom stability	lateral resistance, displacement, safety margin
Decision	MCDA, AHP, fuzzy AHP	criteria, weights, normalization, sensitivity

RESULT AND DISCUSSION

Geotechnical Characteristics of Seabed Sediments

The literature synthesis indicates that S_u is the most consistent parameter in pipeline analysis on soft clay, as it controls bearing capacity, initial embedment, breakout resistance, and cyclic response. Foundational models such as SHANSEP, CPT correlations, and pipe capacity formulations provide a basis for deriving S_u profiles with depth; however, uncertainty remains due to sample disturbance, anisotropy, strain-rate effects, and lateral variability of sediments [4]–[7]. Consequently, using a single average S_u value for the entire corridor may conceal weak zones that locally

determine protection requirements or alignment changes.

Recent research directions are moving toward spatial representation and large-deformation approaches. Numerical studies from 2023–2026 show that initial embedment, strength profile, soil softening, soil density, and trench/backfill configuration can substantially alter lateral resistance [15]–[17]. These findings support the research proposal design, which extracts the geotechnical profile of each candidate route from a three-dimensional stratigraphic model and then compares their statistics and critical conditions, rather than relying solely on corridor-average values.

Hydrodynamic Loads, Wave Transformation, and Scour

Environmental loads on pipelines arise from a combination of drag, inertia, and lift, which are sensitive to water particle velocity and acceleration, pipeline diameter, seabed conditions, and embedment [8]–[11]. In shallow water, wave transformation, shoaling, refraction, breaking, and bathymetric variation cause near-bed loads to not always follow offshore boundary conditions linearly. Therefore, domain-based numerical modeling—such as Delft3D/SWAN, TELEMAC, MIKE, or CFD—is relevant for establishing the spatial distribution of loads along the route.

Scour is an important link between hydrodynamics and geotechnics. Recent numerical studies show that scour onset and tunnel erosion are determined by pressure gradients, jet flow beneath the pipeline, live-bed/clear-water conditions, clearance, and sediment properties [22]–[24]. A recent review on local scour also confirms that gaps remain in 3D scour, cohesive sediment, scaling, self-burial, and scour-vibration interaction [24]. Therefore, in the route selection matrix, hydrodynamic indicators should not stop at H_s or current velocity; the potential for seabed morphological change needs to be treated as a separate risk indicator or as a stability modifier.

Pipe-Soil Interaction and On-Bottom Stability

On-bottom stability is fundamentally a balance between hydrodynamic loads, submerged weight, and soil resistance. The DNV-RP-F109 edition 2021, amended through 2025, covers lateral and vertical stability, while the DNV-RP-F114 edition 2021 provides recommendations for pipe-soil interaction under various exposed and buried pipeline conditions [11], [12]. This means that route assessment must link environmental data with soil parameters at the same location.

Ridlwan et al. [13] demonstrated the application of DNVGL-RP-F109 with CFD verification in an Indonesian case and showed the need for concrete ballast adjustment to meet stability criteria. Another dynamic study used time-domain analysis to show that concrete weight coating, wave-current conditions, and soil resistance control lateral displacement [14]. Meanwhile, recent large-deformation and settlement studies have expanded the focus from initial stability

toward long-term behavior and loading history [16], [17].

The implication for route selection is that geotechnical and hydrodynamic scores should not be summed before their physical response is calculated. A more defensible sequence is: soil data + environmental loads → interaction/stability model → performance indicators (e.g., safety factor, displacement, embedment, or stabilization requirements) → normalization into MCDA. This chained structure reduces the risk of double counting and ensures that AHP weights operate on indicators that already carry engineering meaning.

Multi-Criteria Approaches for Route Selection

MCDA provides a framework for comparing routes across criteria with different units. AHP offers a weighting mechanism through pairwise comparison and consistency ratio, while fuzzy AHP can be used when boundaries between categories are imprecise [18]–[20]. However, the quality of results depends heavily on the criteria structure, relative independence among indicators, consistency of the expert panel, and weight sensitivity analysis.

Studies in Indonesia and Southeast Asia demonstrate the benefits of comparative approaches. Novico et al. [20] compared three HDPE pipeline routes in North Maluku using bathymetric surveys, tides, sediment sampling, and hydrodynamic modeling; the second route was selected because of lower hydrodynamic exposure and more uniform lithology. Kamajaya and Handiani [25] mapped gas pipeline route hazards in Batam using MBES and side-scan sonar and identified extreme slopes, sediment types, sandwaves, and cable crossings. Studies on optimal route selection against submarine landslides also demonstrate the value of a decision-support approach that links geohazard intensity to pipeline response [26].

From these studies, the strongest novelty for the Balongan proposal context is not merely the use of AHP, but rather the integration sequence: spatial sediment modeling → derivation of geotechnical parameters → wave-current modeling → on-bottom/pipe-soil response analysis → indicator normalization → AHP/weighted aggregation → sensitivity analysis. With this structure, the final ranking can be traced back to the physical processes that shape the risk.

Table 2. Synthesis of key studies and their relevance to the research framework

Study	Focus/Method	Relevant Findings	Gap for Integrated Routing
Novico et al., 2021 [20]	3 routes; bathymetry, sediment, MIKE 21	Route selected based on hydrodynamic exposure and lithological uniformity	Has not delved into S_u /pipe-soil interaction
Ridlwan et al., 2022 [13]	DNVGL-F109 + CFD	Ballast affects the fulfillment of stability criteria	Single-route case; not a route comparison
Tofany & Wirahman, 2022 [22]	Two-phase CFD scour	Piping and jet flow control onset/tunnel erosion	Not yet linked to route ranking
Dong et al., 2023 [15]	3D nonlinear FE; trench/backfill	Simplification of soil/pipe can alter response	Focus on response, not routing

Study	Focus/Method	Relevant Findings	Gap for Integrated Routing
Kamajaya & Handiani, 2025 [25]	MBES + SSS + GIS hazard	Slope, sediment, sandwave, cable crossing can be mapped	Not yet integrated with stability calculation
Schreiber, 2025 [27]	Local on-bottom stability	Site-specific input reduces over-stabilization	Local assessment focus on existing pipeline
ASCE study, 2026 [17]	Large-deformation pipe–soil clay	Weight, embedment, strength profile, softening dominate	Has not been translated into a route score

Thematic Synthesis and Research Gaps

Four main gaps were identified. First, the spatial variability of S_u and stratigraphy is often reduced to a representative value, even though a long route may traverse facies with different responses. Second, the distribution of wave–current and scour potential is often analyzed separately from local soil characteristics. Third, many stability studies focus on a single alignment, so they do not directly address the route selection question. Fourth, MCDA often aggregates raw criteria without first linking them through a physical stability model.

Based on this synthesis, the recommended conceptual framework is a four-level hierarchy: (1) baseline data: bathymetry, stratigraphy, CPT/lab, wave–current, obstacles/crossings; (2) derived parameters: S_u profile, bearing capacity, KC, hydrodynamic force, scour

susceptibility; (3) performance indicators: vertical/lateral stability, displacement, embedment, stabilization requirement, constructability; and (4) decision score: AHP/MCDA with sensitivity analysis. This structure aligns with the Balongan research proposal, which aims to compare three candidate routes on an equal basis through the integration of geotechnics and hydrodynamics.

A limitation of this review is that n in the PRISMA diagram cannot yet be determined solely from the reference list of the research proposal. These numbers must come from the final database search export, accompanied by deduplication, a log of full-text exclusion reasons, and an auditable study matrix. Therefore, n is not estimated in this article to avoid unverifiable methodological claims.

Table 3. Research gaps and development directions

Aspect	Literature Limitation	Proposed Direction
Geotechnics	Discrete points / average values	3D stratigraphic model and S_u profile per route
Hydrodynamics	Loads and scour often separated	Spatial distribution of wave–current + scour susceptibility
Stability	Predominantly single-route	Performance indicators calculated for all candidates
MCDA	Aggregation of raw criteria	MCDA on performance outputs to reduce double counting
Validation	Limited site-specific models	Cross-check of standards, numerical, metocean statistics, weight sensitivity

CONCLUSION

This systematic review shows that the feasibility of subsea pipeline routes in shallow waters cannot be assessed from a single group of parameters alone. Undrained shear strength, stratigraphy, embedment, bearing capacity, wave–current loads, and scour potential interact in shaping pipe–soil response and on-bottom stability. DNV standards provide a robust design framework, while recent numerical studies demonstrate the importance of site-specific input and the representation of large-deformation and seabed morphological change. Routing literature demonstrates the benefits of MCDA/AHP, but geotechnical–hydrodynamic integration will be stronger if decision aggregation is carried out after physical parameters have been translated into stability performance indicators. Therefore, the methodological contribution relevant to the Balongan study is a chained framework from spatial characterization, hydrodynamic modeling, and pipe–soil/stability analysis through to MCDA and sensitivity analysis, in order to compare candidate routes in a measurable and traceable manner.

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