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Original Article

Integrating FMEA and BowTie Analysis for Environmental, Social, and Governance Risk Management in Jetty Construction

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Abstract

Marine construction projects expose ecosystems, workers, coastal communities, and project governance to risks that are strongly interdependent but often assessed in separate registers. This study develops an integrated approach using Failure Mode and Effects Analysis (FMEA), a probability-impact matrix, and BowTie analysis to identify, prioritize, and translate environmental, social, and governance (ESG) risks into barrier-based controls for the New Jetty I Project at Manggis Integrated Terminal, Bali. A single-case study combined document review, observation, interviews, a cross-functional expert questionnaire, and a focus group discussion. The panel validated 36 risks and assigned consensus severity, occurrence, and detection scores. Governance produced the highest average Risk Priority Number and the largest concentration of first-priority risks. The dominant concerns involved unresolved community grievances, marine collision, work forced under schedule and weather pressure, restricted marine operating windows, operator fatigue, and weaknesses in barrier governance. Six BowTie scenarios linked these priorities to preventive and mitigative barriers, responsible owners, performance indicators, and escalation thresholds. Residual ratings suggest most risks could be reduced to low or moderate levels, although schedule, weather conflict and limited operating time still required stronger treatment. The findings show that FMEA becomes more decision-relevant when combined with consequence-based matrix judgment and BowTie barrier verification. The integrated FMEA-BowTie model provides a traceable way to embed ESG risk into marine project decisions.

Keywords: BowTie Analysis, Environmental Social and Governance, Failure Mode and Effects Analysis, Jetty Construction, Project Risk Management.

1. Introduction

Ports, terminals, jetties, and their access infrastructure support energy security and regional trade, yet their construction takes place at the boundary between industrial operations and sensitive coastal systems. Piling, dredging-related sediment disturbance, vessel movement, bunkering, heavy lifting, and material handling can affect water quality, underwater sound, marine habitats, navigation, and occupational safety. These same activities can also alter fishing access, disrupt local routines, and challenge customary values, generating community grievances in the process. These exposures are not independent. A weather decision can change lifting safety and spill probability; an unannounced marine closure can affect fishers and trigger protest; a procurement decision can weaken an environmental barrier. Guidance for ports therefore treats pollution prevention, safe navigation, emergency readiness, workforce protection, and community engagement as connected management responsibilities rather than isolated technical tasks (IFC, 2012, 2017; ILO, 2018).

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The governance dimension is especially important in a project environment. Environmental approval, marine-space conformity, vessel legality, contractor selection, budget protection, stop-work authority, management of change, monitoring, disclosure, and grievance handling all depend on how decisions are assigned and evidenced. ISO 31000, IEC 62198, and ISO 21502 together frame risk management as an integrated, continually improved process that connects risk treatment to project objectives, responsibilities, information, and change control (IEC, 2025; ISO, 2018, 2020). From an ESG perspective, this means that technical controls cannot be considered reliable merely because they appear in a method statement. Their owners, resources, performance criteria, triggers, records, and corrective actions must also be visible.

Research on sustainable construction and port infrastructure has identified broad categories of environmental and social exposure, stakeholder expectations, and governance practices (Coskun et al., 2023; Galvao et al., 2025; Jiang et al., 2023; Lam & Yap, 2019). Studies of coastal sediment disturbance show that the severity of ecological effects depends on exposure intensity, duration, hydrodynamics, and receptor sensitivity (Erftemeijer et al., 2012; Jones et al., 2016). Marine construction also creates livelihood and access concerns for small-scale fishers whose operational territory overlaps with project space (Gasalla & Gandini, 2016). Nevertheless, project risk registers often retain a functional separation: environmental risks are assigned to HSE staff, safety risks to construction teams, social risks to stakeholder-relations personnel, and governance risks to managers or commercial functions. Such separation makes it difficult to see how a single loss-of-control event can cross several ESG pillars.

Failure Mode and Effects Analysis (FMEA) offers a systematic way to compare failure modes through severity, occurrence, and detection. Its conventional Risk Priority Number (RPN) is easy to communicate, but equal RPNs may represent different risk profiles and the multiplication rule can conceal a catastrophic consequence behind a low occurrence score. Reviews and improved FMEA models have therefore emphasized the need to retain the component scores, acknowledge uncertainty, and supplement RPN ranking with other decision criteria (Li et al., 2022; Liu et al., 2013). IEC 60812 similarly treats prioritization as an aid to treatment decisions rather than an automatic substitute for judgment (IEC, 2018).

BowTie analysis addresses a different question. Instead of ranking many risks, it organizes one critical scenario around threats, a top event, consequences, preventive barriers, and mitigative barriers. Its visual logic has been applied to maritime collision, construction sustainability, and marine transport hazards because it shows where prevention should stop loss of control and where recovery should limit consequences (Hsu et al., 2023; Temel et al., 2024; Trindade et al., 2020). However, BowTie does not by itself determine which ESG scenarios deserve attention first. The two techniques are therefore complementary: FMEA supports prioritization, while BowTie converts selected priorities into testable barrier requirements.

This study examines the New Jetty I construction project at Manggis Integrated Terminal in Bali, Indonesia. The project occupies marine space shared by terminal operations, project vessels, local jukung, fishing activity, coastal communities, and customary practices. It asks three questions: which ESG risks are material to the construction context; how should they be prioritized when RPN, probability-impact level, and ESG consequences are considered together; and which preventive and mitigative barriers are required for the most decision-relevant scenarios. This study contributes an integrated FMEA-BowTie model that links ESG risk prioritization with barrier ownership and performance indicators.

2. Literature Review

2.1. ESG Risk in Marine Infrastructure

ESG provides a useful lens for organizing project uncertainty, but its value lies in the connections among its pillars. Environmental risks in jetty construction include suspended sediment, underwater noise, fuel or hydraulic-oil release, waste entering the sea, invasive species associated with ballast water, unstable marine equipment, material loss, and emissions. Social risks include occupational injury, fatigue, employment conditions, public safety, fishing access, gear damage, customary activities, communication, and grievance escalation. Governance risks arise when approvals, spatial conformity, vessel requirements, procurement, budget, schedules, authority, monitoring, audit, disclosure, or stakeholder commitments are not translated into operational decisions. GRI materiality and IFC performance standards both direct attention to impacts on people and the environment, including impacts linked to business relationships and contractors (GRI, 2021; IFC, 2012).

In port sustainability practice, policies, programs, projects, processes, and partnerships must reinforce one another (Galvao et al., 2025). A sediment barrier, for example, is an environmental control, but its effectiveness depends on procurement specifications, installation quality, inspection, weather limits, monitoring, and stop-work authority. A safe fishing route is a social safeguard, but it depends on marine coordination, communication, patrols, and a credible remedy process. Governance thus operates as the mechanism through which environmental and social commitments become resourced, authorized, monitored, and corrected. Indonesian environmental and spatial regulations reinforce this relationship by linking environmental approval, impact management, spatial planning, and marine-space utilization to evidence of compliance, as set out in Government Regulation Number 21 of 2021 on the Implementation of Spatial Planning, Government Regulation Number 22 of 2021 on the Implementation of Environmental Protection and Management, and Ministry of Marine Affairs and Fisheries Regulation Number 28 of 2021 on the Implementation of Marine Spatial Planning.

2.2. FMEA and Consequence-Sensitive Prioritization

FMEA identifies a failure mode, its causes, effects, existing controls, and three conventional attributes. Severity represents the seriousness of the consequence; occurrence represents the likelihood or frequency of the event; and detection represents the difficulty of identifying the problem before the effect develops. The product of these scores produces the RPN. When the scales are clearly defined, the method supports a transparent comparison across heterogeneous risks and directs attention to weak detection as well as high consequence (IEC, 2018). This feature is valuable for ESG because some failures, such as ballast-water noncompliance or stakeholder distrust, may remain latent until their effects become difficult to reverse.

Equal RPNs may mask different risk structures, since ordinal scales are multiplied as if their intervals were equal and a high-severity risk can be pushed downward when occurrence or detection is low (Li et al., 2022; Liu et al., 2013). Severity, occurrence matrices, and documented expert judgment are therefore needed to elevate risks involving fatality, regulatory breach, irreversible impact, or unacceptable social consequence; this does not eliminate subjectivity, but it makes the basis of judgment visible.

2.3. BowTie Analysis and Barrier Performance

BowTie begins with a top event which is the point at which control over a hazard is lost rather than with the final accident. Threats and preventive barriers appear on the left side; consequences and mitigative or recovery barriers appear on the right. The distinction matters because a barrier that reduces the probability of losing containment has a different function from a barrier that limits ecological damage after a release. Clear functions also allow each barrier to be assigned an owner, performance standard, inspection method, trigger, and evidence record.

Maritime applications demonstrate the importance of communication, navigation information, monitoring, competence, and organizational control alongside physical protection. Hsu et al. (2023) used BowTie to structure ship-collision causation and response, while Temel et al. (2024) emphasized expert judgment and uncertainty in maritime barrier analysis. Trindade et al. (2020) showed that BowTie can clarify obstacles and defenses in sustainable construction. These studies support a barrier-management interpretation which a listed barrier is not automatically an effective one. It becomes credible only when it is specific to a threat or consequence, independent enough to interrupt the pathway, resourced, verified, and linked to action when performance falls below its standard.

2.4. Integrated Analytical Framework

The framework used in this study follows a sequence from context to evidence. Project documents, field observations, interviews, and stakeholder inputs create the initial ESG register. Expert validation tests whether each risk is relevant and clearly worded. FMEA then supplies a comparable S-O-D profile and RPN, while the probability-impact matrix protects against rankings that understate severe or unacceptable consequences. The combined result selects critical scenarios for BowTie analysis. BowTie, in turn, converts a priority into threats, barriers, consequences, owners, indicators, and escalation points. Planned treatment produces a target residual rating, which remains provisional until monitoring and implementation evidence demonstrate performance. Figure 1 presents this sequence.

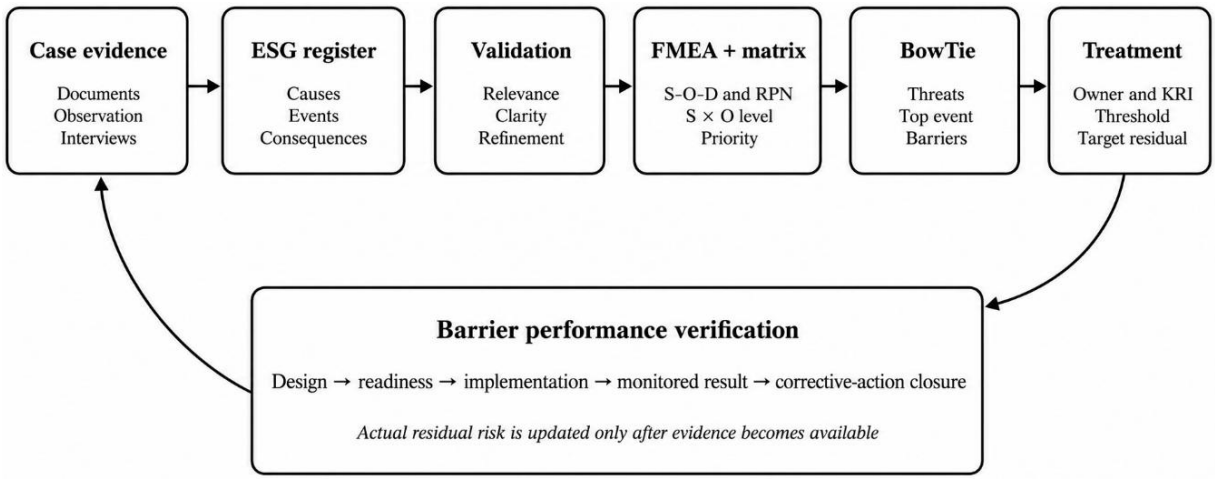


Figure 1. Integrated FMEA-BowTie Analytical Framework
Source: Developed by the author (2026)

3. Methods

3.1. Research Design and Case Context

The research used an embedded single-case design with qualitative and semi-quantitative components. The case was the construction of New Jetty I at Manggis Integrated Terminal, Karangasem, Bali. PT Pertamina Patra Niaga was the project owner and PT Wijaya Karya (Persero) Tbk. was the construction contractor. The unit of analysis was the ESG risk-management process during construction, testing, and early operational preparation. The case was selected because marine construction, terminal activity, local navigation, fishing livelihoods, and customary practices occupied the same operational setting. A case design was appropriate for tracing how technical exposure and organizational decisions interacted within a real project (Joubert & Pretorius, 2020; PT Wijaya Karya, 2026).

Evidence came from the consolidated research instrument, the project report, observations, interviews, questionnaire scoring, and a focus group discussion (FGD). The project report provided work context, schedule and risk themes, while literature and standards supplied analytical criteria. Corporate risk scores in the project report were not converted into FMEA values because the two systems used different definitions and scales. Triangulation was limited to risk themes, exposure, control status, and documentary evidence. Table 1 summarizes the evidence and its analytical function.

Table 1. Data Sources and Analytical Functions

Source	Principal content	Analytical function
Project documents and report	Design, activities, schedule, existing risk themes, approvals, actions	Context definition and documentary triangulation
Observation	Marine work, equipment, interfaces, existing barriers, stakeholder setting	Verify exposure and practical control conditions
Interviews	Causes, effects, control gaps, roles, local concerns	Develop and refine the ESG risk register
Expert questionnaire	Relevance, clarity, severity, occurrence, detection	Validate risks and calculate consensus FMEA scores
Focus group discussion	Score rationale, priority, BowTie pathways, treatment and targets	Reach documented consensus and define barrier requirements
Standards and literature	Risk-process criteria, ESG impacts, FMEA and BowTie principles	Provide an interpretive framework without replacing case evidence

Source: Complied by the author (2026)

3.2. Expert Panel and Risk Validation

Purposive sampling was used to assemble a twelve-person cross-functional panel. Participants represented project management, engineering, construction, marine operations, planning and control, supply chain or procurement, HSE, an independent consultant, port authority functions, sectoral regulation, and social or community perspectives. The composition was designed to cover decision authority, technical exposure, compliance, and affected-stakeholder knowledge rather than to produce a statistically representative survey. This use of purposive sampling follows the logic that information-rich participants are selected for their relevance to the research journey and decision context (Ahmad & Wilkins, 2024).

The preliminary register was developed from project documents, field information, interviews, and literature. Each item contained a code, ESG pillar, activity, cause, risk event,

consequence, existing barrier, and initial owner. The panel assessed relevance on a four-point scale and clarity as clear or requiring revision. All items were retained after discussion. Twenty-six obtained a consensus relevance score of four, while ten obtained a score of three and were refined. For each item, only the final consensus relevance value and the final consensus S-O-D set were recorded in the consolidated file; individual expert rating sheets were not retained. Consequently, item-level or scale-level content-validity indices and inter-rater dispersion were not calculated. This reporting choice avoids presenting a consensus record as if it were a distribution of independent observations.

3.3. FMEA Scoring and Priority Rules

The validated register comprised ten environmental, twelve social, and fourteen governance risks. Panel members discussed severity (S), occurrence (O), and detection difficulty (D) using operational definitions on a one-to-five scale. Severity ranged from minor and reversible impact to catastrophic, fatal, major-regulatory, or irreversible consequence. Occurrence ranged from rare to very frequent under the project conditions. Detection ranged from almost certain early detection to a condition that was unlikely to be identified before the effect developed. After differences were discussed in the FGD, one consensus integer score was recorded for each factor. The RPN was calculated as:

$$RPN = S \times O \times D \quad (1)$$

Arithmetic was independently checked for all risk rows. The severity-occurrence matrix used S × O to classify low, moderate, high, or very-high risk. The third quartile of the observed RPN distribution was 48. A risk entered Priority I when its RPN reached that threshold or its matrix level was very high. Priority II included risks that still required directed treatment because of severity, detection difficulty, legal obligation, or a distinctive environmental or social consequence. Remaining risks were assigned to monitoring. The FGD could elevate a risk when a numerical ranking failed to represent an unacceptable consequence. The full S, O, and D profile was retained so that equal RPNs were not interpreted as equivalent risk structures.

3.4. BowTie Development and Residual Targets

Six BowTie scenarios were selected using the FMEA decision, matrix level, cross-pillar consequence, project evidence, and the panel's judgment of what would be unacceptable to lose control over. Selection was therefore not limited to the six largest RPNs. For each scenario, the FGD defined the top event, threats, preventive barriers, consequences, and mitigative barriers. Barriers were then linked to an owner, target, key risk indicator (KRI), escalation threshold, and evidence requirement. This structure followed IEC 31010 guidance on selecting risk-assessment techniques and the barrier logic used in maritime and construction applications (Hsu et al., 2023; IEC, 2019; Trindade et al., 2020).

The panel also prepared response actions and target S-O-D scores for twenty selected risks. Target residual scores were interpreted as planning values after additional treatment, not as measured post-control performance. Residual risk assessment requires evidence of design adequacy, readiness, implementation, and monitoring, together with closure of corrective action over an adequate observation period. Research permission was obtained from the relevant project authority, the purpose and confidential use of data were explained, and participant identities were not attached to individual scores in the analysis.

4. Results and Discussion

4.1. ESG Risk Profile

The validated register contained thirty-six risks: ten environmental, twelve social, and fourteen governance. Environmental risks followed the physical pathways of marine work. Suspended sediment could spread beyond the work zone; pile installation could generate underwater noise; fuel or hydraulic oil could reach the water; waste or material could be lost overboard; ballast-water practices could introduce organisms; and unstable barges or cranes could create combined pollution, safety, asset, and schedule consequences. The register also included emissions and supply-chain data because the project's environmental boundary extended beyond visible site conditions.

Social risks covered workers and coastal stakeholders. Work at height over water, heavy lifting, fatigue, and emergency readiness shaped workforce exposure. For communities, the relevant pathways were obstruction of jukung routes and fishing grounds, damage to fishing gear, perceived disruption of sacred space or customary activities, inadequate communication, and unresolved grievances. These findings are consistent with research showing that small-scale fisheries depend on access to operational territories and that port sustainability is partly judged through stakeholder relationships, not only infrastructure output (Gasalla & Gandini, 2016; Lam & Yap, 2019).

Governance risks described how commitments could fail in practice. They included inconsistent implementation of environmental plans, nonconformity with marine-space approval, vessel legality, collision control, vendor capability, reduced barrier quality, unsafe schedule pressure, delayed decisions, distrust of project information, late detection of barrier failure, lack of cross-stakeholder acceptance, domestic-content and material constraints, and limited marine operating time. The high number of governance items did not simply reflect administrative paperwork. Each item represented a decision mechanism that could strengthen or weaken environmental and social barriers.

4.2. FMEA Priorities and the Value of Combined Judgment

The RPN distribution differed substantially across the three pillars. Governance had the highest mean and median, at 45.64 and 48, and contained nine of the fourteen Priority I risks. Social risks had a mean of 36.67 and included four Priority I risks, while environmental risks had a mean of 31.50 and one Priority I risk. The environmental range was narrower, whereas social and governance risks extended to the highest RPN values. Governance risks produced the highest concentration of Priority I items, highlighting the importance of decision mechanisms in ESG risk control. Table 2 reports the pillar-level profile, and Figure 2 shows the distributions and Priority I codes against the third-quartile threshold.

Table 2. FMEA Profile by ESG Pillar

Pillar	n	Mean RPN	Median	Range	Priority I	Priority II	Monitor
Environmental	10	31.5	31	20-40	1	6	3
Social	12	36.67	32	27-64	4	7	1
Governance	14	45.64	48	30-60	9	5	0

Source: Processed data (2026)

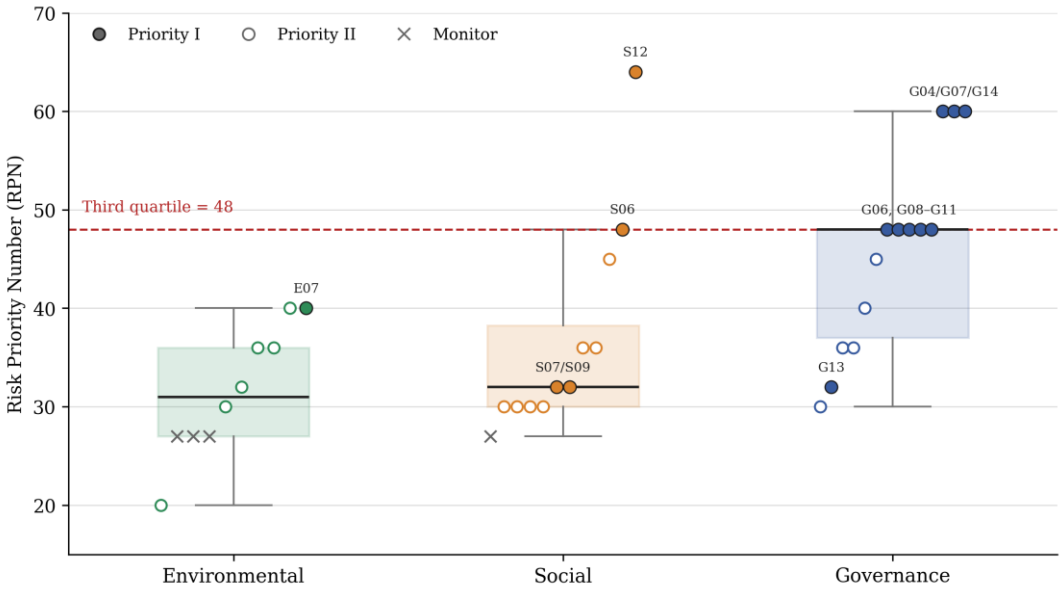


Figure 2. Distribution of Risk Priority Numbers across ESG Pillars
Source: Processed data (2026)

Unresolved and escalating community grievances (S12) produced the highest RPN at 64. Three governance risks followed at 60: marine collision (G04), work forced under unsafe schedule or weather conditions (G07), and reduced effective piling time with conflict among marine operations (G14). Operator fatigue (S06) and six governance risks reached an RPN of 48. These governance items concerned degraded barriers, delayed or contradictory decisions, distrust, delayed detection of failure, and insufficient cross-stakeholder acceptance. Table 3 lists every Priority I risk selected through the combined rule.

Table 3. Priority I Risks Selected by the Combined FMEA-Matrix Rule

Code	Pillar	Risk event	S	O	D	RPN	Matrix level
S12	Social	Unresolved community grievances that escalate	4	4	4	64	Very high
G04	Gov.	Collision involving a barge, vessel, facility, or marine user	5	4	3	60	Very high
G07	Gov.	Work is forced under unsafe conditions or creates a time dispute	5	4	3	60	Very high
G14	Gov.	Effective piling time is reduced and conflicts with marine operations	4	5	3	60	Very high
S06	Social	Operator fatigue and reduced alertness	4	4	3	48	Very high
G06	Gov.	Critical barriers are omitted or their quality is reduced	4	3	4	48	High
G08	Gov.	Risk-control decisions are delayed or contradictory	4	3	4	48	High
G09	Gov.	Stakeholders do not trust project controls and information	4	3	4	48	High
G10	Gov.	Changes in risk and barrier failures are detected late	4	3	4	48	High
G11	Gov.	Project decisions lack cross-stakeholder acceptance	4	4	3	48	Very high
E07	Env.	Barge or crane instability while work continues under unsafe conditions	5	4	2	40	Very high

Code	Pillar	Risk event	S	O	D	RPN	Matrix level
S07	Social	Disruption of *jukung* routes and fishing grounds	4	4	2	32	Very high
S09	Social	Perceived disturbance to sacred space, *Melasti*, or *awig-awig*	4	4	2	32	Very high
G13	Gov.	Domestic-content requirements or material constraints delay completion	4	4	2	32	Very high

Note. Priority I includes an RPN at or above the third quartile or a very-high severity-occurrence matrix level. Env. = Environmental; Gov. = Governance; S = severity; O = occurrence; D = detection difficulty.

Source: Processed data (2026)

The component scores explain why a ranking based only on RPN would be misleading. Ballast-water risk (E05) and unstable barge or crane operation (E07) both had an RPN of 40. E05 was driven by a detection score of five because a problem may not be apparent before ecological effects emerge. E07 combined maximum severity with high occurrence and therefore reached a very-high matrix level. Oil or fuel release (E03) had a comparatively low RPN of 20 but remained in Priority II because severity was five and the event could cause widespread pollution, regulatory action, and work stoppage. Conversely, disruption of fishing routes (S07) and customary activities (S09) entered Priority I through their very-high matrix level even though each RPN was 32.

This reinforces the criticism that conventional FMEA compresses distinct causal and consequence profiles into a single score (Li et al., 2022; Liu et al., 2013). The combined rule did not discard RPN; it made RPN auditable and bounded its use. The third-quartile threshold provided a consistent ranking rule, the matrix protected severity including occurrence combinations, and FGD documentation preserved legal, environmental, and social reasoning, consistent with IEC 60812 (IEC, 2018).

4.3. BowTie Scenarios and Barrier Architecture

The six BowTie scenarios covered two environmental loss events, two marine-operation loss events, one social-acceptance event, and one compliance event, together connecting risks that would otherwise remain in separate functional registers. Table 4 summarizes the top events and critical preventive and mitigative barriers for each scenario.

Table 4. BowTie Scenarios and Critical Barrier Functions

ID	Linked risks	Top event	Critical preventive barriers	Critical mitigative or recovery barriers
BT-01	E01	Uncontrolled suspended-sediment plume	Staged piling; double silt curtain; tensile and condition checks; turbidity trigger	Stop-work; reinforce containment; monitoring; joint investigation and recovery
BT-02	E03	Oil or fuel reaches the marine environment	Vessel inspection; preventive maintenance; drip trays; controlled bunkering; vendor due diligence	Oil boom and spill kit; isolation; notification; sampling; recovery and compensation
BT-03	E07, S01, S02	Loss of control during marine	Weather limits; stop-work authority; lifting certification; fit-to-	Rescue and medevac; exclusion zone; tug assistance;

ID	Linked risks	Top event	Critical preventive barriers	Critical mitigative or recovery barriers
		work or heavy lifting	work; one-command communication	environmental recovery; claim records
BT-04	G04	Loss of safe separation among project and local vessels	Notice to Mariners; VHF checks; marine coordinator; buoys; patrols; vessel legality checks	Search and rescue; spill response; traffic rerouting; evidence preservation; regulator reporting
BT-05	S07, S09, S12, G11	Loss of community and stakeholder acceptance	Participatory mapping; safe routes; compensation procedure; customary calendar; GRM with service level	Multi-party mediation; joint investigation; livelihood remedy; commitment tracking; public communication
BT-06	G01, G02, G10	Work departs from environmental or marine-space commitments	Compliance register; hold points; management of change; field audit; calibrated monitoring dashboard	Stop-work; corrective action; renewed approval; legal review; remediation and independent verification

Source: Processed data (2026)

Across the six scenarios, a consistent pattern emerged: preparedness measures (e.g., spill kits, search and rescue) were treated as recovery barriers rather than substitutes for prevention, and each barrier was linked to a specific threat or consequence rather than listed generically. The suspended-sediment and oil-release scenarios (BT-01, BT-02) relied on staged work, inspection, and monitoring to prevent loss of containment, with rapid containment and remedy as recovery functions (Erftemeijer et al., 2012; Jones et al., 2016). The marine-operation scenarios (BT-03, BT-04) depended on weather limits, stop-work authority, and marine coordination as preventive barriers, and on rescue, spill response, and regulator reporting as recovery functions, consistent with maritime BowTie research showing that navigation and communication are barriers only when responsibility, timing, and verification are explicit (Hsu et al., 2023). Figure 3 presents the barrier architecture for loss of safe marine separation (BT-04) as an illustrative example.

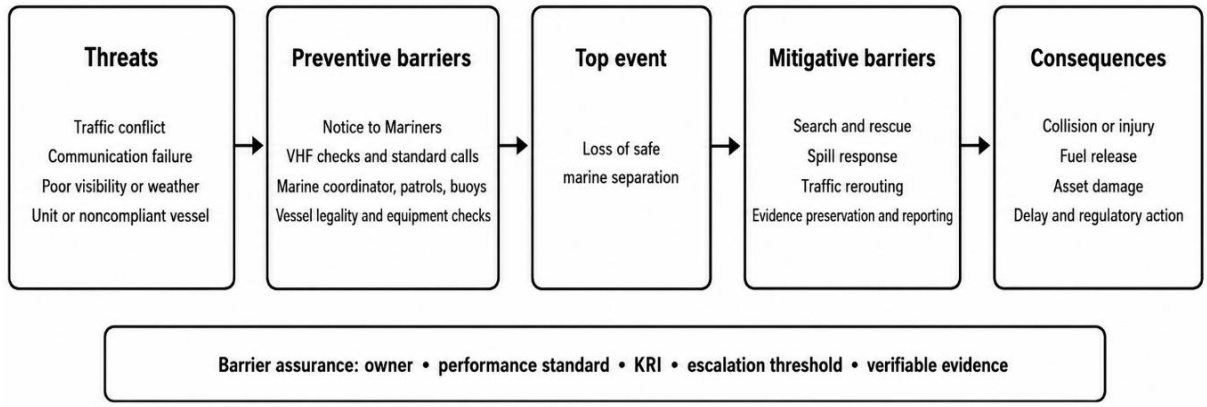


Figure 3. BowTie Barrier Architecture for Loss of Safe Marine Separation (BT-04)

Source: Processed data (2026)

The stakeholder-acceptance scenario (BT-05) placed participatory mapping, protected routes, and a grievance mechanism with a defined response time as preventive barriers, with mediation and livelihood remedy as recovery functions, positioning social acceptance within operational risk management rather than as a general communication objective. The compliance scenario (BT-06) linked approval conditions to field decisions through a compliance register, hold points, and management of change, with stop-work and corrective action as recovery functions, showing that compliance is a chain of evidence rather than a static document status.

4.4. Treatment Strategy and Target Residual Risk

Risk reduction was the most common response because marine construction activities could not simply be removed from the project scope. Reduction combined engineering measures, inspections, competence, communication, monitoring, stakeholder engagement, audits, and contract controls. Avoidance was applied when work would exceed weather limits, proceed without approval, use unfit equipment, or continue without the acceptance required for a sensitive activity. Transfer through insurance, vendor obligations, and contractual mechanisms allocated financial or delivery consequences but did not transfer the project's duty to verify barriers.

The twenty-risk target set initially contained nine very-high, six high, and five moderate ratings. After planned treatment, the target profile comprised five low and thirteen moderate ratings; two governance risks remained high. Those two were unsafe schedule-weather pressure (G07) and restricted effective piling time amid marine operating conflicts (G14). Their target RPNs fell but did not reach the acceptance range because their occurrence could not be reduced solely through site-level controls. They required schedule contingency, owner-contractor alignment, protected stop-work authority, weather-window planning, terminal coordination, and timely commercial decisions.

The target profile must not be read as evidence that barriers had already worked. Severity generally remained unchanged because a procedure or monitoring device does not remove the worst credible consequence. Planned reductions came mainly from lower occurrence through prevention and lower detection scores through inspection, alarms, records, and audit. Actual residual risk should be confirmed only after evidence shows barrier design, readiness, implementation, performance, and corrective-action closure. Relevant evidence includes turbidity results, silt-curtain condition, vessel inspections, radio checks, stop-work records, rescue or spill-response time, grievance service levels, audit closure, and KRI trends. Taneja et al. (2021) similarly noted that port-sustainability performance is constrained when indicator data are unavailable or disconnected from decisions.

4.5. Theoretical and Managerial Implications

Governance risks require barrier ownership and escalation thresholds: the dominant average RPN for governance did not mean it was more important than environmental or social outcomes, but that decisions about authority, time, money, vendors, change, and stakeholder commitments determined whether those outcomes were protected.

Integrating FMEA with BowTie ensures that ESG risks are not only prioritized but also translated into actionable barrier requirements. For project managers, the results support three decision horizons. Daily control should integrate weather, marine traffic, work permits, critical lifts, barrier condition, monitoring, and grievances in one operational briefing. Weekly review should examine KRI trends, overdue actions, changes, vendor performance, fishing or customary commitments, and emerging schedule pressure. Monthly governance should address compliance, protected ESG budgets, audit findings, residual-risk evidence, and multi-

stakeholder issues. A hold point should be released only when permits, competence, communication, weather, equipment, community commitments, and response readiness are evidenced for the relevant scenario.

A practical dashboard should distinguish leading from lagging indicators. Leading indicators include silt-curtain integrity, calibrated monitoring availability, weather exceedance forecasts, radio-check completion, equipment certification, working hours, unresolved commitments, and approaching permit deadlines. Lagging indicators include spills, exceedances, injuries, repeated complaints, damaged fishing gear, major findings, and work stoppage. Assigning each indicator an owner, threshold, and escalation route changes ESG reporting from retrospective disclosure into a mechanism for intervention.

4.6. Limitations

The findings come from one jetty project and should be transferred analytically rather than statistically to other locations. The consolidated dataset retained final consensus scores but not the individual expert sheets; therefore, medians, interquartile ranges, content-validity indices, and disagreement patterns could not be reconstructed. Project-report risk ratings were not merged numerically with FMEA because their scales differed. The residual values were treatment targets rather than observations after implementation. Future studies should retain individual ratings, test barrier performance over time, and compare construction and operating phases using environmental monitoring, incident, fatigue, navigation, grievance, compliance, and audit data.

5. Conclusion

The study shows that ESG risk in jetty construction is produced by the interaction of marine work, environmental receptors, workforce safety, fishing livelihoods, customary values, regulatory commitments, contracts, and organizational decisions. The most consequential priorities were not limited to visible environmental hazards. Unresolved grievances, marine collision, unsafe schedule pressure, limited operating windows, fatigue, weakened barriers, delayed decisions, distrust, and insufficient cross-stakeholder acceptance formed the central risk pattern.

The integrated FMEA-BowTie approach enhances ESG risk management in marine construction by combining prioritization with barrier verification. Governance risks emerged as the most critical, underscoring the need for transparent decision-making and stakeholder trust. FMEA made the broad register comparable, the matrix preserved severe and unacceptable consequences, and BowTie translated selected priorities into threat-specific preventive and mitigative barriers. The resulting barrier system joined technical controls with stop-work authority, marine coordination, stakeholder engagement, compliance, budget protection, audit, indicators, thresholds, and evidence of performance.

For practice, ESG risk management should be embedded in operational and commercial decisions rather than managed as a separate reporting stream. Target residual ratings remain conditional until implementation and monitoring demonstrate that barriers are ready, used, effective, and corrected when they fail. This evidence-based interpretation allows project teams to update priorities as design, weather, vessels, schedules, contractors, access arrangements, and stakeholder commitments change. This study is limited to a single case; future research should test the framework across multiple marine infrastructure projects.

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5.2. Competing Interests

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6. References

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