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# Optimization of the Western Surabaya Shipping Channel Design Based on Semi-Quantitative Risk Analysis for Navigation Risk Level Reduction

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**Abstract**

*The Western Surabaya Shipping Channel (APBS) serves as Indonesia's primary logistics gateway to Eastern Indonesia. Despite its 2014 revitalization, 27 shipping accidents occurred between 2014–2024, indicating persistent navigation safety gaps. This study aims to optimize APBS design through a semi-quantitative risk analysis approach to reduce navigation risk levels in eight critical segments. The methodology integrates hydro-oceanographic data, ship traffic, historical accidents, and expert judgment from six experts (harbor pilots, KSOP, Navigation District), using a 5×5 risk matrix with Analytical Hierarchy Process (AHP) weighting. Results show that the Channel Geometry Factor (CGF) dominates risk contribution (45%), followed by Exposure Frequency (23%), Environmental Conditions (20%), and Historical Accident Factor (12%) (CR = 0.077). Of 15 identified hazards, 80% are classified as Unacceptable. The combined optimization scenario (deepening, widening, geometry improvement, and shipwreck evacuation) reduces 91.7% of hazards to ALARP/Acceptable levels. However, minimum design standards (width 200 m, depth –14 mLWS, radius 4×LOA) are insufficient for Segment 3, leaving a residual risk score of R' = 16. Additional interventions radius ≥1,000 m (5×LOA), deepening to –15 mLWS, and a one-way system are required. This research concludes that risk-based APBS optimization effectively reduces navigation risk but necessitates interventions beyond conventional minimum standards. The findings provide actionable recommendations for policymakers and port authorities in enhancing maritime safety and operational efficiency.*

## Introduction

The Western Surabaya Shipping Channel (APBS) constitutes one of the national strategic maritime infrastructures, serving as the main logistics gateway to Eastern Indonesia. The existence of APBS is critical in determining the smooth flow of goods, logistics cost efficiency, and national supply chain stability. As the primary logistics gateway for Eastern Indonesia, the performance of Tanjung Perak Port, Surabaya, serves not only as a regional economic indicator but also as a pillar of the national supply chain. Significant performance growth is reflected in the average increase in cargo loading and unloading throughput of 5–7% per annum, which demands the availability of a safe, efficient shipping channel capable of accommodating the evolving dimensions of modern vessels (Heikkilä et al., 2024; Papanikolaou et al., 2022).

The strategic role of APBS is reinforced through its designation as part of the national shipping lane system based on Minister of Transportation Decree Number KP 455 of 2016 concerning the Determination of Route Systems, Traffic Procedures, and Ship Anchorage



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Areas in the Western Surabaya Shipping Channel. This regulation emphasizes the importance of sustainable navigation safety management, as APBS serves as the primary route for commercial vessel movements to and from eastern Indonesia (Riyadi & Erliyani, 2025; Julianto et al., 2025; Pamungkas, 2024). Consequently, any disruption to APBS operations has the potential to cause widespread economic impacts, both on logistics costs and on the availability of goods across various regions of Indonesia (Wahyuni et al., 2025; Anas et al., 2022; Makruf & Riani, 2025).

The drive for global economic efficiency has triggered an increase in vessel dimensions, leading the Government, through the Ministry of Transportation, to revitalize APBS in 2014 by widening the channel from 100 meters to 150 meters and deepening it from -9.5 mLWS to -13 mLWS. This policy significantly increased vessel traffic projections through 2041, from 27,000 to 74,000 vessels, and opened direct shipping routes to China and Europe without the need for transshipment at other ports. This change directly reduced logistics costs and enhanced the competitiveness of national products.

Nevertheless, the increase in the channel's physical capacity has not been fully accompanied by a comprehensive evaluation of operational dynamics involving increasingly larger vessel dimensions, increased traffic density, and changes in water environmental conditions (Wan et al., 2024; Zhuang et al., 2024; Huang & Ung, 2023; Zhao et al., 2025). Although APBS capacity has significantly increased, safety challenges have become increasingly complex. According to the Ship–Channel–Environment (S-C-E) concept developed by PIANC, navigation safety is influenced by the interaction between ship characteristics, shipping channel geometry, and water environmental conditions (PIANC, 2014; Paulauskas et al., 2022; Liu et al., 2022; Bąk et al., 2024; El-Tawil et al., 2026 ). Consequently, shipping channel design must not only consider the channel's physical dimensions but must also integrate ship characteristics and environmental factors simultaneously (Kim & Roh, 2025; Maljković et al., 2024; Jiang et al., 2026; . Imbalance among these three components has the potential to increase the probability of shipping accidents, particularly in channels with geometric limitations and high traffic density (Zhu et al., 2025; Shi et al., 2024; Chen et al., 2025; Yu et al., 2022).

Empirical evidence shows that during the ten-year post-revitalization period (2014–2024), at least 27 ship accident incidents still occurred in the APBS area. Ship-to-ship collisions were the most dominant type of accident (47.4%), followed by fires (31.6%), sinkings (18.4%), and groundings (5.3%). An average of 2–3 incidents still occurred each year despite the channel having been widened and deepened. Historical data analysis reveals significant spatial patterns, with 14 incidents concentrated in eight critical segments (Younes & Oloufa, 2025; Feng et al., 2025; Soltani et al., 2024). The majority of accidents involved vessels over 500 GT and were concentrated in segments with complex geometric characteristics, such as sharp-radius bends, large channel junction angles, and crossing areas with dense ferry traffic

In addition to geometric factors, navigation risk in APBS is also influenced by dynamic environmental conditions. High sedimentation rates cause periodic changes in the channel's effective depth, thereby reducing the under keel clearance (UKC) of vessels, particularly those with large drafts (Kadir et al., 2025; Łazuga, 2025). On the other hand, relatively high current speeds and the dominance of beam winds have the potential to increase vessel maneuvering difficulties in certain segments. Concurrently, the growth in the number of large vessels and increased traffic density are projected to continue rising over the next two decades, thereby posing new challenges for navigation safety management (Hebbar et al., 2024; Magkos, 2025; Maharaj et al., 2025).

Various previous studies have examined APBS safety aspects from the perspectives of hydro-oceanography, sedimentation, and collision risk analysis using the Formal Safety Assessment



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(FSA) approach. However, most of these studies remain partial in nature and have not integrated environmental factors, channel geometry, ship characteristics, and traffic conditions into a single comprehensive evaluation framework (Damastuti et al., 2025; Purba et al., 2020; Saputro et al., 2023). This limitation means that the resulting recommendations cannot yet be directly applied to shipping channel design optimization based on actual risk levels.

To address this gap, this study employs a semi-quantitative risk analysis approach that combines the advantages of both qualitative and quantitative methods. This approach enables the utilization of expert judgment from harbor pilots, the Port Authority and Harbor Master's Office (KSOP), and the Navigation District, which is then converted into numerical scores, thereby producing more objective risk measures that can be compared across segments (Kim et al., 2023; Mousavi et al., 2017). The analysis is conducted through the measurement of four main risk factors, namely Environment Factor (EF), External Condition Factor (ECF), Channel Geometric Factor (CGF), and Historical Accident Factor (HAF), thus enabling the generation of a risk map that can serve as a basis for formulating shipping channel design optimization scenarios.

Despite the strategic importance of APBS, previous studies have examined navigation safety from fragmented perspectives focusing separately on hydro-oceanography (Saputro et al., 2023), sedimentation modeling (Zahra et al., 2024), or collision risk using Formal Safety Assessment (Purba et al., 2020). However, none of these studies have integrated all three Ship-Channel-Environment (S-C-E) components into a unified semi-quantitative risk framework that simultaneously considers channel geometry, environmental dynamics, traffic characteristics, and historical accident records. Consequently, prior recommendations remain partial and cannot be directly translated into channel design optimization based on actual risk levels. This research gap underscores the need for a comprehensive risk-based evaluation that can guide structural interventions in APBS design.

Based on the above description, this study aims to optimize the design of the Western Surabaya Shipping Channel through a semi-quantitative risk analysis approach to reduce navigation risk levels in critical APBS segments. Specifically, the research objectives are: (1) to map navigation risk profiles across 8 critical APBS segments through the identification of 15 priority hazards; (2) to identify the dominant factors influencing navigation risk levels; (3) to test the effectiveness of design optimization scenarios in reducing risk levels; and (4) to produce strategic recommendations and an implementation roadmap. The research results are expected to provide a scientific contribution to the development of risk-based shipping channel design evaluation methodologies, while also serving as strategic recommendations for the government, port operators, and maritime stakeholders in enhancing the safety and operational efficiency of national shipping.

## Methods

### Research Design

This study employs a semi-quantitative risk analysis approach to evaluate navigation risk levels and formulate design optimization scenarios for the Westren Surabaya Shipping Channel (APBS). This approach was selected because it is capable of integrating quantitative data on hydro-oceanographic conditions, channel geometry, ship traffic, and ship accident history with qualitative assessments from experts (expert judgment), thereby producing a more comprehensive risk assessment compared to purely quantitative or qualitative methods. The research framework refers to the ISO 31000:2018 risk management standard as well as the Formal Safety Assessment (FSA) recommended by the International Maritime Organization (IMO).



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**Research Location and Time**

The research was conducted at the Western Surabaya Shipping Channel (APBS), located in the Madura Strait, East Java Province. The shipping channel has a length of 39.65 Nautical Miles (NM) or 73.5 km and serves as the main access route to Tanjung Perak Port, Teluk Lamong Terminal, Gresik Port, and various Terminals for Own Use (TUKS) in the Gresik–Surabaya area. The research focuses on 8 critical segments as designated by Minister of Transportation Decree Number KP 455 of 2016 and validated by experts.

Table 1. Research Location (APBS Critical Segments)

| No | Critical Area | Coordinate Position | Navigation Buoy Area | Description | Number Of Incidents |
|---|---|---|---|---|---|
| 1 | Critical Segment 1 | 6° 51' 43.8600" S / 112° 44' 42.5200" E to 7° 00' 57.7140" S / 112° 40' 28.8820" E | Buoy no. 2 to 15 | Main APBS dredging area, high sedimentation, lateral current 1.4 m/s, length 19 km | 2 incidents |
| 2 | Critical Segment 2 | 6° 51' 43.8600" S / 112° 44' 42.5200" E to 6° 53' 25.4738" S / 112° 44' 06.3570" E | Buoy no. 2 to 4 | Junction of branching channels, angle >60°, turbulent currents | 3 incidents |
| 3 | Critical Segment 3 | 6° 57' 27.7554" S / 112° 42' 40.1198" E to 6° 58' 56.0785" S / 112° 41' 53.3109" E | Buoy area no.10 to buoy no.12 or buoy no.11 to buoy no.13 | Rede Buoy 10 bend, radius <3×LOA | 5 incidents |
| 4 | Critical Segment 4 | 6° 59' 55.2980" S / 112° 41' 11.9309" E to 7° 00' 57.7140" S / 112° 40' 28.8820" E | Around buoy no.14 to no.15 | Last main dredging area, sudden depth transition, caution at vessel meeting entry/exit | 0 incidents (high near-miss) |
| 5 | Critical Segment 5 | 7° 04' 35.4755" S / 112° 39' 31.2503" E to 7° 05' 43.5048" S / 112° 39' 27.0313" E | Approaching buoy no.18 to buoy no.19 area | Bend area near TUKS Berlian Manyar Sejahtera, dock distance 350m | 1 incident |
| 6 | Critical Segment 6 | 7° 07' 13.0324" S / 112° 39' 31.4420" E to 7° 08' 27.9416" S / 112° 39' 56.7286" E | Buoy no.20 to KM. Dewaruci wreck buoy area | Shallow water at 6 mLWS and KM. Dewaruci wreck | 1 fatal incident |
| 7 | Critical Segment 7 | 7° 10' 28.6111" S / 112° 40' 53.9028" E to 7° 11' 21.2041" S / 112° 42' 04.9572" E | Pisang buoy area to buoy no.22 | Bend near Teluk Lamong Terminal on the south side of the channel and anchorage area on the north side of the channel | 1 incident |
| 8 | Critical Segment 8 | 7° 11' 21.2041" S / 112° 42' 04.9572" E to 7° 11' 32.2700" S / 112° 44' 02.9500" E | Buoy no.22 to buoy no.26 | In Segment 8, there is a container terminal to the south, an anchorage area to the north, a terminal pool entrance, and a ferry crossing from Ujung Tanjung | 2 incidents |



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| | | | | | |
|---|---|---|---|---|---|
| | | | | Perak Pier to Kamal Port (Madura) | |

Table 2. Research Timeline

| Month | Activity | Brief Description | Output |
|---|---|---|---|
| Month 1 | Preparation and Initial Data Collection | Literature and regulation review. Secondary data collection: bathymetry, hydro-oceanography, AIS data, accident data. | Literature and regulation database; structured secondary data collection |
| Month 2 | Data Processing and Hazard Identification | Environmental and traffic data processing. Hazard identification in critical APBS segments. | Processed data; list of identified hazards per segment |
| Month 3 | Semi-Quantitative Risk Analysis | Probability and consequence assessment using 5×5 risk matrix. Risk score calculation per segment. | Risk score and risk level per segment; risk map of existing conditions |
| Month 4 | Optimization Scenario Development | Simulation of channel width and depth variations. Mitigation recommendation design. | 4 optimization scenarios; impact simulation of each scenario |
| Month 5 | Scenario Evaluation and Results Analysis | Comparison of risk scores before and after optimization. Scenario effectiveness analysis. | Comparison matrix of risk scores; scenario ranking |
| Month 6 | Report and Article Writing | Final report writing. Journal article writing. | Thesis report; journal article draft |

**Types and Sources of Data**

The research uses a combination of primary and secondary data. Primary data were obtained through an expert judgment process involving six experts consisting of 2 APBS harbor pilots with >10 years of experience piloting ships in APBS, 2 officials from the Main Port Authority and Harbor Master's Office (KSOP) Tanjung Perak with experience in traffic supervision and accident investigation, and 2 officials from the Tanjung Perak Type I Class A Navigation District with experience in channel maintenance and Navigation Aids (SBNP). Meanwhile, secondary data were obtained from ship accident investigation reports from KSOP Utama Tanjung Perak, PT Pelindo, PT Alur Pelayaran Barat Surabaya, the Meteorology Climatology and Geophysics Agency (BMKG), as well as Minister of Transportation Decree (KM) Number 19 of 2024 establishing the Integrated Port Master Plan for Tanjung Perak Port and Gresik Port. The data used include: 1) Hydro-oceanographic data including currents, wind, tides, and sedimentation; 2) Channel geometry data including channel width, depth, turning radius, and channel junction angles; 3) Ship traffic data including vessel visits, vessel dimensions, and traffic growth projections; 4) Ship accident data for the 2014–2024 period; and 5) Operational condition data and navigation aids facilities; 6) Surabaya West Shipping Channel Maintenance Report Data.



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### Data Collection Techniques

Data collection was conducted through three main stages, namely literature study and documentation, secondary data collection from relevant agencies, and expert judgment implementation. The literature study was conducted to obtain theoretical foundations regarding shipping channel design, maritime risk management, and international navigation safety standards. Furthermore, expert judgment was used to validate hazard identification using the FMEA method, determine probability and consequence levels using the Australian/New Zealand Standard AS/NZS 4360:2004, and perform risk factor weighting using the Analytical Hierarchy Process (AHP) method.

### Expert Profile and AHP Implementation

Expert judgment was obtained from six maritime professionals, each with more than 10 years of operational experience in the APBS area: 1) 2 harbor pilots – experienced in ship maneuvering under various weather and traffic conditions; 2) 2 officials from KSOP Utama Tanjung Perak – responsible for traffic supervision and accident investigation; 3) 2 officials from the Tanjung Perak Navigation District (DISNAV) – in charge of channel maintenance and navigation aids.

The AHP pairwise comparison was conducted using Saaty's 1–5 scale, where experts compared the relative importance of four risk factors (EF, ECF, CGF, HAF) in pairs. Individual judgments were aggregated using the geometric mean to produce a consensus matrix. Consistency was verified using the Consistency Ratio (CR), with $CR < 0.1$ considered acceptable (Saaty, 2008).

### Data Analysis Stages

#### *Hazard Identification*

The first stage of the research was hazard identification using the Failure Mode and Effects Analysis (FMEA) method combined with the Hazard Identification Worksheet (HAZID). This process aimed to identify potential navigation failures in each critical APBS segment along with their causes and consequences. The identification results produced 15 priority hazards that were subsequently analyzed using a semi-quantitative approach.

### Semi-Quantitative Risk Analysis

Risk analysis was conducted using a 5×5 risk matrix combining event probability and severity levels. Probability values were obtained through a combination of four main factors, namely: a) Exposure Frequency (EF); b) Environmental Condition Factor (ECF); c) Channel Geometry Factor (CGF); and d) Historical Accident Factor (HAF).

Weighting of these four factors was conducted using the Analytical Hierarchy Process (AHP) method based on pairwise comparison matrices. Subsequently, probability scores were calculated using Equation (1):

$$PS = \frac{(EF \times w_1) + (ECF \times w_2) + (CGF \times w_3) + (HAF \times w_4)}{w_1 + w_2 + w_3 + w_4}$$

where:

$PS$ = Probability Score;

$w_i$ = weight of each factor from AHP results;

$EF$ = Exposure Frequency;

$ECF$ = Environmental Condition Factor;

$CGF$ = Channel Geometry Factor;



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$HAF$ = Historical Accident Factor.

Probability values were then converted to a 1–5 probability scale and multiplied by consequence scores to produce Risk Scores using the Australian/New Zealand Standard AS/NZS 4360:2004 with the following equation:

$$R = P \times S$$

where:

$R$ = Risk Score;

$P$ = Probability of occurrence;

$S$ = Severity level.

Risk level classification was conducted based on the As Low As Reasonably Practicable (ALARP) principle into categories of Acceptable, ALARP, and Unacceptable.

**Risk Mapping**

The obtained risk scores were then spatially mapped across the eight critical APBS segments using a Geographic Information System (GIS) approach to produce a risk map. The risk map was used to identify locations with the highest risk levels and determine priorities for channel design interventions.

**Optimization Scenario Evaluation**

The study evaluated four design optimization scenarios, namely: a) Scenario A: channel deepening from −13 mLWS to −14 mLWS; b) Scenario B: channel widening from 150 m to 200 m accompanied by turning radius and channel junction angle improvements; c) Scenario C: shipwreck evacuation in Segment 6; and d) Scenario D: combination of all previous scenarios.

The effectiveness of each scenario was measured using Absolute Risk Reduction (ARR) and Relative Risk Reduction (RRR) indicators as well as the ALARP status achievement level. The scenario with the greatest risk reduction and most realistic implementation level was selected as the main recommendation for future APBS development.

**Supporting Software**

Data analysis and processing were conducted using several supporting software applications, including Microsoft Excel for statistical data processing and risk calculations, AHP software for risk factor weighting, and Geographic Information System (GIS) for spatial mapping of risk levels in APBS.

## Results and Discussion

**Identifikasi Hazard**

Based on the synthesis of secondary data and expert judgment validation, 15 priority hazards were identified across 8 critical APBS segments. Table 1 presents a summary of the validated hazards.

**Hazard Coding System**

Each hazard is coded using the format: H[Segment]-[Component]-[Sub-component][Threat] , where:

Component: C = Channel, E = Environment, T = Traffic;

Sub-component: 1 = Geometry, 2 = Maneuvering space, 3 = Depth, 4 = Hazardous object;

Threat: Co = Collision, G = Grounding, D = Drifting, etc.



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*Example*: H3-C1-CoG = Hazard in Segment 3, Channel component, Geometry sub-component, with Collision and Grounding threats.

Table 3. Recapitulation of 15 Priority Hazards in APBS

| Segment | Hazard Code | Hazard Description | Threat Type | Hazard Source |
|---|---|---|---|---|
| 1 | H1-C1-DGCo | Combination of 19 km segment length with lateral current | D, Co | Geometry (C) |
| 1 | H1-E3-G | Dynamic shoaling due to high sedimentation | G | Environment (E) |
| 2a | H2-T1-Co | Collision risk from branching | Co | Traffic (T) |
| 2a | H2-E1-DCo | Complex currents at channel junction | D, Co | Environment (E) |
| 3 | H3-C1-CoG | Very critical turning radius (201-206 m) | Co, G | Geometry (C) |
| 3 | H3-C2-GD | Bank effect at sharp bends | G, D | Geometry (C) |
| 3 | H3-T2-Co | Large vessels difficulty passing each other | Co | Traffic (T) |
| 4 | H4-C4-G | Sudden depth change | G | Geometry (C) |
| 5 | H5-C2-Co | Limited maneuvering space in front of TUKS | Co | Geometry (C) |
| 6 | H6-C3-G | Critical depth in mound area | G | Geometry (C) |
| 6 | H6-C4-G | KM Dewaruci wreck at 75m distance | G | Geometry (C) |
| 7 | H7-E2-D | Beam wind 7.6 m/s from West/Southwest | D | Environment (E) |
| 8 | H8-T1-Co | Ferry crossing conflict | Co | Traffic (T) |
| 8 | H8-T3-Co | Ship interaction at pool entry/exit | Co | Traffic (T) |
| 8 | H8-C2-Co | Bend area near anchorage zone | Co | Geometry (C) |

Based on the hazard identification results, navigation risks in the Western Surabaya Shipping Channel (APBS) are primarily triggered by non-conformities in the Channel and Environment components, which then increase the hazard potential in the Ship component, thus empirically strengthening the Ship–Channel–Environment (S-C-E) framework. The highest hazard concentration was found in Segments 3 and 8, which have the most significant channel geometry limitations, indicating that narrow channel design, sharp bends, and environmental conditions such as currents and sedimentation are the main factors driving navigation risk. Physical channel limitations are also proven to correlate with increased ship traffic conflicts, thereby increasing the likelihood of accidents. The dominance of hazards with Unacceptable status at 80% indicates that existing APBS conditions are at a risk level that cannot be addressed solely through operational procedures and crew vigilance. Furthermore, collision hazards reaching 60% of total hazards confirm that collisions are the main safety threat in APBS, as reflected in KSOP historical accident data. Therefore, improving navigation safety in APBS requires fundamental interventions through physical channel design improvements and comprehensive water environment management to significantly reduce risk levels (Negi et al., 2024; Alsubaih et al., 2025; Wang et al., 2026; Anishkumar et al., 2026).

**Determination of Factor Weights Using AHP**

The weighting results using the Analytical Hierarchy Process (AHP) method combined assessments from all experts (Pilots, KSOP, and DISNAV), using geometric means. The result is a consensus matrix representing the collective assessment as shown in the following table:



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Table 4. Final Results of Probability Factor Weights

| Factor | Code | Weight (w) | Weight (%) |
|---|---|---|---|
| Exposure Frequency | EF | 0.23 | 23% |
| Environmental Conditions | ECF | 0.20 | 20% |
| Channel Geometry | CGF | 0.45 | 45% |
| Accident Track Record | HAF | 0.12 | 12% |
| Total | | 1.00 | 100% |

Consistency Ratio (CR) = 0.077 (< 0.1) → Consistent

Based on the weighting results, the Channel Geometry Factor (CGF) is the main determinant of navigation risk in the Western Surabaya Shipping Channel (APBS) with a weight contribution of (45%), followed by Exposure Frequency (EF) at 23%, Environmental Conditions (ECF) at 20%, and Accident Track Record (HAF) at 12% with a Consistency Ratio (CR) = 0.077, indicating a good level of assessment consistency. This finding confirms that the condition and physical design of the channel have the most dominant influence on shipping safety levels and validates the research hypothesis that channel geometry is the main foundation in navigation risk control. The dominance of the geometry factor indicates that non-structural mitigation efforts such as adding Navigation Aids (SBNP), optimizing pilot procedures, and improving VTS coordination have limited effectiveness if not accompanied by improvements to the channel's physical aspects. Thus, the root cause of navigation risk in APBS is not solely in operational aspects, but primarily in the limitations of the shipping infrastructure design itself. Therefore, the most effective and sustainable mitigation strategy must prioritize structural interventions in the form of channel widening, deepening beyond existing design according to operational needs, and turning radius improvements to achieve significant and sustainable navigation risk reduction in APBS.

**Risk Score Calculation**

To facilitate priority analysis, a recapitulation of Risk Scores by critical segment was conducted by calculating the average Risk Score for each segment.

Table 5. Recapitulation of Risk Scores per APBS Critical Segment

| Segment | Location | Number Of Hazards | Range Of R | Average R | Priority |
|---|---|---|---|---|---|
| Segment 1 | Long Sedimentation Area | 2 | 16-20 | 18.0 | Rank 1 |
| Segment 6 | KM Dewaruci Wreck Area | 2 | 16-20 | 18.0 | Rank 1 |
| Segment 3 | Rede Buoy 10 Bend | 3 | 16-20 | 17.3 | Rank 1 |
| Segment 8 | Ferry, Terminal, Anchorage Zone Area | 3 | 16 | 16.0 | Rank 2 |
| Segment 2a | Channel Branching | 2 | 16 | 16.0 | Rank 2 |
| Segment 7 | Teluk Lamong Bend | 1 | 9 | 9.0 | Rank 3 |
| Segment 4 | Depth Transition | 1 | 9 | 9.0 | Rank 3 |
| Segment 5 | Near TUKS Manyar | 1 | 9 | 9.0 | Rank 3 |

Based on the established criteria, the acceptability status was determined for each hazard.

Table 6. Risk Acceptability Status for 15 Hazards in APBS

| Risk Status | Number of Hazards | Percentage | Hazard List |
|---|---|---|---|
| Unacceptable | 12 | 80.00% | H1-C1-DGCo, H1-E3-G, H2-E1-DCo, H2-T1-Co, H3-C1-CoG, H3-C2-GD, H3-T2- |



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| | | | |
|---|---|---|---|
| | | | Co, H6-C3-G, H6-C4-G, H8-T1-Co, H8-T3-Co, H8-C2-Co |
| ALARP | 3 | 20.00% | H4-C4-G, H5-C2-Co, H7-E2-D |
| Acceptable | 0 | 0% | - |

Based on the analysis results, navigation risk conditions in the Western Surabaya Shipping Channel (APBS) are at a very critical level, as indicated by 12 out of 15 hazards (80.00%) falling into the Unacceptable category. This finding shows that existing APBS conditions have exceeded risk tolerance limits and cannot be maintained without significant corrective action. The dominance of hazards in this category confirms that non-structural mitigation strategies implemented so far, such as adding Navigation Aids (SBNP), optimizing pilot procedures, improving Vessel Traffic Service (VTS) coordination, and routine patrols, have reached their effectiveness limits in substantially reducing risk. Therefore, risk management in APBS can no longer be addressed through gradual operational improvements but requires more fundamental changes through structural interventions in the shipping channel geometry. This finding simultaneously reinforces the urgency of implementing channel design optimization as a strategic step to achieve significant, sustainable navigation risk reduction in accordance with required shipping safety levels.

**Spatial Risk Mapping**

To visualize the spatial distribution of risk along the APBS, spatial mapping was conducted by grouping the analyzed segments according to their average risk levels. Each segment was classified into a corresponding risk category based on the calculated mean risk score, allowing areas with relatively low, moderate, and high risk to be clearly distinguished. This spatial representation provides a clearer understanding of how risk varies along the APBS and helps identify priority segments that may require greater attention, monitoring, or mitigation measures.

Table 7. Spatial Risk Mapping of APBS

| Segment | Location | Average R | Risk Level | Color Code |
|---|---|---|---|---|
| Segment 1 | Long Sedimentation Area | 18.0 | Very High | 🔴 RED |
| Segment 6 | KM Dewaruci Wreck Area | 18.0 | Very High | 🔴 RED |
| Segment 3 | Rede Buoy 10 Bend | 17.3 | Very High | 🔴 RED |
| Segment 8 | Ferry, Terminal, & Pool Entry/Exit Area | 16.0 | Very High | 🔴 RED |
| Segment 2a | Channel Branching | 16.0 | Very High | 🔴 RED |
| Segment 7 | Teluk Lamong Bend | 9.0 | Medium | 🟡 YELLOW |
| Segment 4 | Depth Transition | 9.0 | Medium | 🟡 YELLOW |
| Segment 5 | Near TUKS Manyar | 9.0 | Medium | 🟡 YELLOW |



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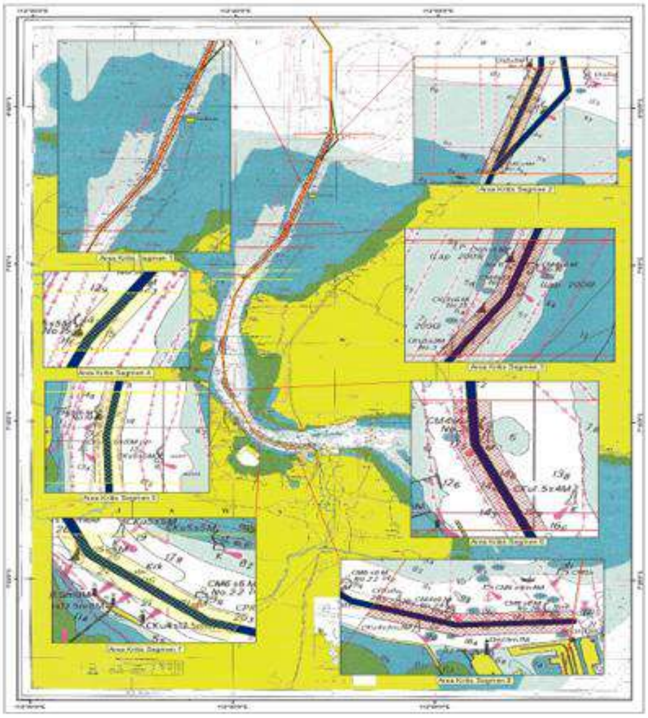

*Figure 1. Visual APBS Risk Map*

**Optimization Scenario Evaluation**

Table 8. Description of APBS Design Optimization Scenarios

| Scenario Code | Scenario Name | Intervention Description | Target Segment | Parameters Modified |
|---|---|---|---|---|
| S-A | Channel Deepening | Deepening from -13 mLWS to -14 mLWS | Segments 1, 6 | Depth (CGF) |
| S-B | Channel Widening & Geometry Improvement | Widening 150m→200m, turning radius improvement ≥800m | Segments 2a, 3, 8 | Width, radius, angle (CGF) |
| S-C | Permanent Hazard Evacuation | KM Dewaruci wreck evacuation | Segment 6 | Hazard removal (CGF) |
| S-D | Combined Scenario | Combination of A+B+C | All segments | All CGF parameters |

Based on the analysis results, the APBS design optimization scenarios were developed with an approach focused on improving the Channel Geometry Factor (CGF) aspects as the dominant factor shaping navigation risk. Four intervention scenarios were developed to address various physical channel limitations identified during the risk analysis stage. Scenario S-A focused on increasing vertical capacity through channel deepening from -13 mLWS to -14 mLWS in critical segments with depth limitations. Scenario S-B was directed at increasing horizontal capacity and ship maneuverability through channel widening from 150 meters to 200 meters and turning radius improvement to a minimum of 800 meters, especially in segments with the highest traffic conflict and geometric limitations. Scenario S-C focused on eliminating permanent hazard sources through evacuation of the KM Dewaruci wreck, which has been a navigation obstacle. Meanwhile, Scenario S-D is a comprehensive approach integrating all interventions from previous scenarios, thus covering all channel geometry parameters contributing to navigation risk.



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Overall, this series of scenarios demonstrates that navigation risk reduction in APBS cannot be achieved solely through operational measures but requires structural interventions in the physical channel design. The combined scenario (S-D) is projected to provide the greatest mitigation impact as it can simultaneously address various risk factors arising from channel geometry limitations and permanent obstacles in the shipping area.

Table 9. Effectiveness Analysis of Scenario D (Combination A+B+C)

| Segment | Hazard Code | R Existing | P' | S' | R' (P'×S') | Arr | Rrr | Final Status | Remark |
|---|---|---|---|---|---|---|---|---|---|
| 1 | H1-C1-DGCo | 20 | 4 | 2 | 8 | 12 | 60% | Medium (ALARP) | Achieved |
| 1 | H1-E3-G | 16 | 4 | 2 | 8 | 8 | 50% | Medium (ALARP) | Achieved |
| 2a | H2-T1-Co | 16 | 3 | 2 | 6 | 10 | 62.5% | Medium (ALARP) | Achieved |
| 2a | H2-E1-DCo | 16 | 3 | 2 | 6 | 10 | 62.5% | Medium (ALARP) | Achieved |
| 3 | H3-C1-CoG | 20 | 4 | 4 | 16 | 4 | 20% | High (Unacceptable) | Not Yet ALARP |
| 3 | H3-C2-GD | 16 | 4 | 2 | 8 | 8 | 50% | Medium (ALARP) | Achieved |
| 3 | H3-T2-Co | 16 | 4 | 2 | 8 | 8 | 50% | Medium (ALARP) | Achieved |
| 6 | H6-C3-G | 16 | 3 | 2 | 6 | 10 | 62.5% | Low (Acceptable) | Achieved |
| 6 | H6-C4-G | 20 | 3 | 2 | 6 | 14 | 70% | Low (Acceptable) | Achieved |
| 8 | H8-T1-Co | 16 | 4 | 2 | 8 | 8 | 50% | Medium (ALARP) | Achieved |
| 8 | H8-T3-Co | 16 | 4 | 2 | 8 | 8 | 50% | Medium (ALARP) | Achieved |
| 8 | H8-C2-Co | 16 | 4 | 2 | 8 | 8 | 50% | Medium (ALARP) | Achieved |
| Average | | | | | | **9** | **53.12%** | | |

Based on the analysis results, Scenario D, which combines channel deepening, widening and geometry improvement, and permanent hazard evacuation, is the most effective mitigation alternative in reducing navigation risk levels in the Western Surabaya Shipping Channel (APBS). Implementation of this scenario resulted in an average Absolute Risk Reduction (ARR) of 9 points and Relative Risk Reduction (RRR) of 53.12%, indicating a significant risk reduction compared to existing conditions. Of the total 12 priority hazards analyzed, 11 hazards (91.7%) were successfully reduced to Acceptable or ALARP risk levels, while only 1 hazard, namely H3-C1-CoG in Segment 3, remained in the Unacceptable category with a residual risk score of 16. This finding indicates that although the structural interventions implemented have provided substantial mitigation impact, the geometric characteristics and traffic complexity in Segment 3 still require additional handling beyond the designed optimization scenarios.

The greatest effectiveness was achieved in Segment 6, particularly for hazards H6-C4-G and H6-C3-G, with risk reductions of 70% and 62.5% respectively, confirming that channel deepening and permanent obstacle removal are highly effective strategies for reducing navigation risk in areas with depth limitations and the presence of obstructing objects. Meanwhile, hazards related to traffic conflicts and geometric limitations in Segments 2a and 8 were also successfully reduced to ALARP levels with average risk reduction above 55%. Overall, these results prove that mitigation approaches based on structural interventions in channel geometry are far more effective than operational or non-structural approaches alone.



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Thus, Scenario D can be recommended as the optimal alternative for improving shipping safety in APBS, although further evaluation and possible additional interventions in Segment 3 are needed to ensure all hazards can reach acceptable risk levels according to the As Low As Reasonably Practicable (ALARP) principle.

**Comparison with Previous Studies**

The dominance of the Channel Geometry Factor (45%) in this study aligns with findings from PIANC (2014), which emphasizes that channel width, depth, and turning radius are primary determinants of navigation safety in restricted waterways. However, while Purba et al. (2020) identified collision risk in APBS using FSA without weighting environmental factors, our study quantifies the relative contribution of each S-C-E component, providing a more nuanced prioritization for design interventions. Compared to similar studies in the Singapore Strait (Montewka et al. (2014) and the Malacca Strait, our results show that sedimentation-induced depth reduction and sharp bends create risk profiles unique to APBS, requiring site-specific solutions rather than generic standard adoption. This finding reinforces the need for revising national channel design standards (PM 129/2016) to accommodate local hydrodynamic and geometric constraints.

**Additional Interventions Required**

Based on the evaluation results, minimum design standards (width 200m, depth -14 mLWS, radius 4×LOA) proved insufficient to address catastrophic hazards in Segment 3. Additional interventions required are as follows:

Table 10. Gaps and Additional Interventions Required

| Segment | Hazard Code | R' Scenario D | Target R (Alarp) | Gap | Priority | Additional Interventions Required | Quantitative Parameters |
|---|---|---|---|---|---|---|---|
| 3 | H3-C1-CoG | 16 | ≤11 | 5 | 1 | Increase turning radius beyond minimum standard | Radius ≥ 1,000 m (5× LOA) → R'=9 (ALARP), ideal 1,200 m (6× LOA) → R'=6 (Acceptable) |
| 3 | H3-C1-CoG | 16 | ≤11 | 5 | 2 | Implement one-way system during peak hours | Applied when >60 vessels/day or draft >12 m; CER=8.0 |
| 3 | H3-C1-CoG | 16 | ≤11 | 5 | 3 | Installation of mooring dolphins at the bend as passive protection | 2 units on the inner side of the bend |

Based on the evaluation results, although Scenario D successfully reduced most hazards to Acceptable or ALARP levels, one hazard still did not meet the risk target, namely H3-C1-CoG in Segment 3 with a residual risk score of 16, above the ALARP maximum limit (≤11). This finding indicates that the geometric conditions and operational complexity at the Rede Buoy 10 bend still require special handling beyond the standard interventions already applied. To achieve acceptable risk levels, additional interventions are required in the form of turning radius increase to ≥ 1,000 m (5× LOA) → R'=9 (ALARP), ideally 1,200 m (6× LOA) → R'=6 (Acceptable), implementation of a one-way system applied when traffic density exceeds 60 vessels per day or when vessels with drafts greater than 12 meters will transit. Based on cost-effectiveness analysis, this scenario has the highest cost-effectiveness ratio (CER) of 8.0,



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making it the most economical interim solution before permanent structural interventions are implemented, as well as installation of two mooring dolphin units to support vessel maneuvering in the bend area. Overall, these results indicate that residual risk management in APBS requires a combination of physical channel design optimization and operational arrangements based on traffic conditions so that all hazards can achieve risk levels according to the As Low As Reasonably Practicable (ALARP) principle.

## Conclusion

Based on the hazard identification results, risk analysis, risk factor weighting, and design optimization scenario evaluation at the Western Surabaya Shipping Channel (APBS), it can be concluded that navigation risk levels in APBS are at a very critical condition, with 12 out of 15 priority hazards (80%) in the Unacceptable category. The highest risks are concentrated in Segments 1, 3, 6, and 8, with the most serious hazards caused by strong lateral currents, very narrow turning radius, and the presence of permanent obstacles near the shipping channel. The research results show that the Channel Geometry Factor (CGF) is the most dominant factor influencing risk levels with a weight of 45%, higher than Exposure Frequency (23%), Environmental Conditions (20%), and Accident Track Record (12%) with a Consistency Ratio (CR) = 0.077 indicating good assessment consistency. This finding confirms that navigation safety in APBS is heavily influenced by the quality of the channel's physical design, especially regarding turning radius, channel depth, and channel width that are still inadequate. Optimization scenario evaluation shows that Scenario D, which combines channel deepening, widening and geometry improvement, and permanent hazard evacuation, is the most effective mitigation alternative, successfully reducing 11 out of 12 priority hazards (91.7%) to ALARP or Acceptable categories. However, hazards in Segment 3 still require additional interventions in the form of turning radius improvement to at least 1,000 meters (5×LOA) and implementation of a one-way system during high traffic density. Overall, this research confirms that improving navigation safety in APBS cannot be achieved solely through operational approaches or non-structural mitigation, but requires planned, integrated structural interventions in the physical channel design oriented toward long-term risk reduction according to the As Low As Reasonably Practicable (ALARP) principle.

Based on the research results, improving navigation safety in the Surabaya West Shipping Channel (APBS) needs to be prioritized through several strategic steps, namely evacuation of the KM Dewaruci wreck in Segment 6 as a short-term emergency measure, channel deepening to −15 mLWS in Segments 1 and 6 supported by routine dredging 2–3 times per year, and improvement of the turning radius in Segment 3 to at least 1,000 meters (5×LOA) to reduce the risk of vessel maneuvering conflicts. As a temporary measure, implementation of a one-way system in Segment 3 during peak hours needs to be conducted until geometric improvements are completed. In addition, evaluation and revision of channel design standards in Minister of Transportation Regulation Number PM 129 of 2016 are needed to better suit water conditions with strong currents, high sedimentation, and high ship traffic density.


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