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Impact of Sedimentation and Navigation Aid Deficiencies on Ship Maneuverability and Grounding Accidents in Maritime Operations

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Abstract: Sedimentation and navigation aid deficiencies constitute two interacting technical hazards that persistently contribute to ship grounding accidents, yet their combined effect on vessel maneuverability remains underexamined in qualitative, multi-stakeholder research. This study investigates how sedimentation levels and navigation aid reliability jointly affect ship maneuverability and grounding risk in Indonesian maritime operations. A qualitative design was employed, drawing on semi-structured interviews and focus group discussions with 20 participants: 2 senior maritime professionals with over 20 years of operational experience, 5 maritime vocational lecturers, and 13 recent maritime graduates. Data were analyzed using a systematic six-phase thematic analysis with intercoder verification (Cohen's kappa $\kappa = 0.81$). The results reveal significant cross-group score differentials: experts rated chart accuracy at 8.9 and under-keel clearance management at 8.5, while graduates scored rudder effectiveness at 7.2 and stopping distance management at 7.1 — identifying these hydrodynamic parameters as the most critically underprepared domains in current vocational training. The study makes three specific contributions. First, it demonstrates empirically that the education–industry gap in sedimentation risk management is most acute in hydrodynamic competency rather than navigational aid familiarity. Second, it identifies real-time monitoring and predictive sediment modeling as the technological interventions with the broadest stakeholder consensus. Third, it proposes a structured curriculum integration pathway for sedimentation risk management in Indonesian maritime polytechnics.

Keywords: sedimentation, navigation aids, ship maneuverability, grounding accidents, maritime safety.

INTRODUCTION

Sedimentation as a Maritime Safety Hazard

Sedimentation in navigable waterways presents one of the most consequential and technically complex hazards in maritime operations. When sediment accumulates in port approaches, river channels, and coastal shipping lanes, the resulting reduction in water depth decreases under-keel clearance, increases hull resistance, impairs propulsion efficiency, and degrades the hydrodynamic responsiveness of steering and braking systems — collectively increasing grounding risk in ways that are dynamic, spatially variable, and often poorly represented in electronic chart data (Hopcraft et al., 2023; Brandt et al., 2024). The scale of this risk is substantiated by high-profile incidents: the 2021 blockage of the Suez Canal demonstrated how shallow-water interactions create catastrophic operational consequences, while the grounding of the Costa Concordia illustrated how navigational margin errors in complex bathymetric environments produce irreversible outcomes. Unlike discrete equipment failures, sedimentation-induced hazards evolve continuously with seasonal and hydrological cycles, creating an operational environment where static chart data systematically lag behind actual depth conditions (Zhang et al., 2014).

Navigation aid deficiencies compound this hazard. Electronic chart systems depend on hydrographic survey data that may not reflect recent sedimentation changes. Physical aids such as buoys and lighted markers are subject to maintenance failures, reducing their reliability in high-sediment, high-traffic environments. Available data indicate that approximately 25 percent of lighted navigation aids experience annual failure rates, and 18 percent of buoys in developing maritime nations are off-station at any given time — creating a navigational uncertainty margin that interacts directly with the reduced hydrodynamic margins that sedimentation produces (Puisa et al., 2021). In Indonesian waters specifically, where river-fed sedimentation in major port approaches is a documented operational challenge, this compound hazard has direct implications for the safety of the dense vessel traffic serving one of the world's largest archipelagic states (Wulandari & Cahyadi, 2025).

The Education–Industry Gap in Sedimentation Risk Management

Despite the operational significance of this compound hazard, maritime vocational education in Indonesia has not systematically integrated sedimentation risk management as a structured competency domain. Current maritime polytechnic curricula address navigational safety primarily through regulation-aligned procedural instruction — covering STCW watchkeeping requirements, chart operation, and collision avoidance — without developing the applied hydrodynamic judgment that sediment-prone operations require (Komaro et al., 2022; Daryono et al., 2023). Graduates entering ports and coastal operations contexts may possess regulatory literacy without the technical intuition to recognize how shallow-water effects are altering their vessel's maneuvering envelope under high-sedimentation conditions. This gap between certified competence and operational readiness for sedimentation-specific risks represents a direct maritime safety concern. Zheng et al. (2025), examining institutional safety learning frameworks, identified assessment-level misalignment — certification systems that mandate safety content but prescribe methods incapable of verifying its operational application — as a systemic safety failure. The present study applies this diagnosis to the sedimentation risk domain.

Maritime education research has confirmed that practitioner groups and educational stakeholders hold systematically different perceptions of competency preparedness. Hattingh et al. (2022), examining aviation competency-based education — a parallel safety-critical domain — found that educators' limited understanding of operational competency requirements had direct safety implications, precisely because the assessment systems they administered could not verify operational readiness beyond procedural recall. Oroh et al. (2023) demonstrated for Indonesian vocational contexts that assessment environment quality — specifically, the proximity of assessment to authentic industry conditions — significantly determines what competencies graduates actually develop. These findings frame the education–industry gap in sedimentation risk management as a systemic structural problem rather than a curriculum content oversight.

Research Objectives and Questions

No prior qualitative study has examined the perceptions of maritime professionals, lecturers, and graduates simultaneously regarding sedimentation's hydrodynamic effects and navigation aid reliability — the combined multi-stakeholder analysis that can reveal where the operational competency gap is largest and most consequential. This study addresses that gap. Three research questions structure the investigation: **(RQ1)** What are the hydrodynamic impacts of sedimentation on ship maneuverability as assessed by maritime professionals, lecturers, and graduates? **(RQ2)** How reliable are current navigation aids in preventing grounding accidents, and what improvements are necessary? **(RQ3)** What are the real-world implications of sedimentation and navigation aid deficiencies for maritime vocational education, and what curriculum reforms can address identified competency gaps?

Literature Review

Hydrodynamic Effects of Sedimentation on Ship Maneuverability

Sedimentation's hydrodynamic effects on ship maneuverability operate through several interacting physical mechanisms. Reduced under-keel clearance — the vertical distance between the vessel's keel and the seabed — creates bank suction effects, alters squat dynamics, and reduces the effectiveness of the stern wave that contributes to propulsive thrust (Zhang et al., 2014). As under-keel clearance decreases below approximately 15 percent of vessel draft, rudder effectiveness diminishes non-linearly, turning circle diameter increases, and stopping distance extends — creating a maneuverability envelope that may be significantly smaller than the navigation channel's geometric dimensions would suggest (Brandt et al., 2024). In sediment-laden conditions, hull resistance increases with water density and viscous interaction with suspended particulate matter, further reducing propulsion efficiency and the vessel's ability to accelerate out of dangerous situations. The cumulative effect of these mechanisms is that a vessel operating in a high-sedimentation channel may require 20 to 40 percent more sea room and time to execute standard avoidance maneuvers compared to deep-water operation — a margin that may not be available in confined port approaches (Puisa et al., 2021).

Godet et al. (2023), examining operational cycles for maritime transportation, established that energy efficiency and operational safety are deeply intertwined in confined waterway contexts where hydrodynamic performance margins are reduced by environmental conditions — a framework directly applicable to sedimentation-affected port approaches where the energy cost of maintaining maneuverability and the safety cost of reduced responsiveness are simultaneously elevated. Agrifoglio et al. (2017), analyzing digital technology applications in maritime operations, demonstrated that real-time data integration from environmental monitoring systems significantly improves operational decision-making in complex maritime environments — an architectural principle applicable to real-time sedimentation monitoring for navigation safety.

Navigation Aid Reliability and Chart Accuracy

Navigation aids — encompassing electronic navigational charts, Global Navigation Satellite Systems, radar, and physical aids such as buoys and lighted markers — provide the positional and bathymetric reference framework within which mariners manage hydrodynamic margins. Their reliability is therefore a direct function of grounding risk: chart data that does not reflect actual sedimentation conditions creates systematic errors in the under-keel clearance calculations that navigators use to determine safe routing (Hopcraft et al., 2023; Zhang et al., 2014). Karakasnaki et al. (2023), examining maritime sustainability across its social dimensions, identified the reliability of operational infrastructure — including navigation systems — as a foundational determinant of seafarer safety and professional wellbeing, establishing that navigation aid deficiencies create not only technical risk but occupational safety and psychological burden for maritime personnel. Oldenburg et al. (2010), examining occupational risks in seafaring, documented that navigational uncertainty in confined and shallow-water environments is among the most psychologically demanding conditions maritime professionals encounter, with direct implications for decision-making quality under the time pressure that developing grounding situations impose.

The maintenance deficit in navigation aids documented by Puisa et al. (2021) is particularly consequential in developing maritime nations, where budget constraints, institutional fragmentation, and jurisdictional complexity create environments where buoy off-station rates and chart update delays are systematically higher than in advanced maritime nations. Nguyen et al. (2023), reviewing disruption management in the maritime industry, identified infrastructure reliability — including navigation aid availability — as a primary source of operational disruption with cascading safety consequences, confirming that the navigation aid maintenance problem is not merely a technical issue but a systemic maritime governance challenge.

Maritime Vocational Education and Sedimentation Risk Competency

The preparation of maritime graduates to manage sedimentation-specific risks involves the intersection of technical hydrodynamic knowledge, operational situational awareness, and regulatory literacy — a multidimensional competency profile that conventional maritime curricula do not systematically develop. Widaningsih et al. (2025), mapping technical competency needs for TVET teachers in the Industry 4.0 era, confirmed that digital monitoring technologies — directly applicable to real-time sedimentation monitoring — represent a competency gap among vocational educators, with downstream implications for graduate preparation. Nidhom et al. (2025), systematically reviewing vocational teacher professional education, established that the interaction among professional competence, institutional support, and working conditions determines whether vocational graduates develop genuine operational capability — a finding that frames the sedimentation risk competency gap as a systemic institutional challenge requiring coordinated intervention across curriculum design, instructor development, and industry partnership. Wahyudi et al. (2025), examining university–industry partnership effectiveness, confirmed that substantive operational engagement — as opposed to formal consultative arrangements — is the variable that actually predicts graduate operational readiness for sector-specific technical challenges. Othman et al. (2025), reviewing digitalisation challenges in TVET, confirmed that emerging monitoring technologies require coordinated institutional investment in faculty capacity and curriculum redesign to produce graduates capable of deploying them in professional contexts.

METHOD

Research Design

This study employed a qualitative research design within an interpretivist paradigm (Creswell & Poth, 2018), appropriate for investigating the experiential and positional dimensions of how sedimentation and navigation aid deficiencies are perceived and managed by stakeholders at different levels of the maritime education-to-practice ecosystem. The qualitative approach was selected for its capacity to capture the nuanced, contextually embedded insights that different stakeholder groups — positioned at the operational demand end (professionals), the pedagogical delivery end (lecturers), and the educational experience end (graduates) — bring to the assessment of maritime safety risks.

Participants and Inclusion Criteria

Participants were selected through purposive criterion sampling ensuring positional authority and experiential grounding relevant to the research questions.

1. **Maritime Professionals (n=2):** Inclusion criteria required minimum 20 years of operational experience in port management, ship operations, or maritime cargo handling with documented direct experience navigating high-sedimentation Indonesian waterways. Both participants had served as senior officers in port management corporations and held maritime safety advisory positions.
2. **Maritime Lecturers (n=5):** Inclusion criteria required active teaching responsibilities in navigation, maritime safety, or port operations subjects with minimum three years of maritime vocational instruction experience. Participants taught across nautical deck engineering and port and shipping management programs at two maritime polytechnics.
3. **Graduates (n=13):** Inclusion criteria required completion of a four-year maritime polytechnic program in nautical deck engineering, naval marine engineering, or port and shipping engineering within the preceding two years, and minimum six months of professional maritime employment in operations involving Indonesian port approaches.

Table 1. Summary of Participant Characteristics

Group	n	Core Qualification	Gender (M/F)	Experience Range
Maritime Professionals	2	Min. 20 yrs port/ship operations, Indonesian waterways experience	2M / 0F	22–31 years
Lecturers	5	Min. 3 yrs maritime safety/navigation instruction	4M / 1F	5–18 years
Graduates	13	4-yr maritime polytechnic; min. 6 months employment	11M / 2F	22–27 years
Total	**20**			

Data Collection

Semi-structured interviews were conducted individually with maritime professionals and lecturers; focus group discussions were conducted with two graduate groups. All professional and lecturer interviews were conducted face-to-face at participants' institutional or professional locations. Graduate focus groups were conducted in hybrid format — one face-to-face and one via Zoom — due to participants' distribution across vessels and port locations. Sessions lasted 60 to 90 minutes. All sessions were audio-recorded with participants' written informed consent and transcribed verbatim within one week. Transcripts were returned to participants for member verification; corrections were incorporated before analysis.

The interview protocol addressed three domains corresponding to the research questions: hydrodynamic effects of sedimentation experienced operationally or studied in curricula; navigation aid reliability and failure experiences; and education-to-practice transition regarding sedimentation and navigation competencies. Each domain contained four to six open-ended questions designed to elicit both technical description and evaluative assessment.

The structured evaluation instrument — a 10-point Likert-type rating scale applied to nine maneuverability and navigation aid indicators — was administered within each interview or focus group session. Participants rated each indicator individually (scale: 1 = very ineffective/inadequate; 10 = very effective/adequate). Table 1 reports group mean scores computed from individual ratings within each stakeholder group. These scores represent participants' perceived effectiveness from their positional vantage points, not objective performance metrics.

Secondary data were collected through document review of maritime accident investigation reports involving Indonesian coastal and port grounding incidents, institutional maritime safety syllabi, and international navigation aid maintenance statistics from published maritime safety organization data.

Thematic Analysis: Six-Phase Procedure

Qualitative data underwent thematic analysis following Braun and Clarke (2006). **Phase 1 (Familiarization):** All 20 transcripts were read twice with researcher notes on patterns and striking participant expressions. **Phase 2 (Open Coding):** Line-by-line coding in NVivo 14 generated 141 initial codes across the dataset. **Phase 3 (Focused Coding and Theme Generation):** Initial codes were grouped by relational pattern into 17 sub-categories and consolidated into four overarching themes: sedimentation hydrodynamic impacts, navigation aid reliability and failure modes, education–industry competency gap, and technological and governance solutions. **Phase 4 (Theme Review):** Themes were validated against the full dataset; two sub-categories were merged following team discussion. **Phase 5 (Theme Definition):** Each theme was assigned a precise analytical definition. **Phase 6 (Cross-Group Comparison and Triangulation):** Coded data were disaggregated by stakeholder group to identify convergences and divergences. A second independent coder coded 20 percent of the transcript corpus; Cohen's Kappa was calculated at $\kappa = 0.81$, indicating strong intercoder agreement (Landis & Koch, 1977). Source triangulation cross-referenced interview findings with accident investigation documents and curriculum materials. Member checking was conducted with one participant per stakeholder group who reviewed preliminary theme summaries.

RESULTS AND DISCUSSION

Results

The analysis generated cross-group score differentials across nine maneuverability and navigation aid indicators and four qualitative themes. Themes were derived through the coding process described in Section 3.4; their credibility was established through intercoder reliability ($\kappa = 0.81$), member checking, and document triangulation.

Quantitative Overview

Table 2. Cross-Group Mean Scores for Sedimentation and Navigation Aid Indicators (Scale 1–10)

Indicator	Expert Mean (n=2)	Lecturer Mean (n=5)	Graduate Mean (n=13)	Overall Mean	Effectiveness (%)	Efficiency (%)
Under-Keel Clearance	8.5	7.6	7.9	8.0	90	88
Hull Resistance	8.2	7.4	7.6	7.8	85	84
Propulsion Efficiency	8.0	7.1	7.4	7.5	80	78
Rudder Effectiveness	7.5	7.3	7.2	7.3	75	73
Turning Circle Diameter	7.8	7.5	7.3	7.5	78	76
Stopping Distance	7.2	7.0	7.1	7.1	70	68
Chart Accuracy	8.9	8.0	8.2	8.4	92	90
Buoy Reliability	8.5	7.6	7.8	7.9	88	86
Aid Maintenance Consistency	7.9	7.4	7.6	7.6	82	80

The highest scores appear in Chart Accuracy (overall mean 8.4; effectiveness 92%) and Buoy Reliability (8.5 expert, 88% effectiveness) — navigation aid domains where recent technological investments have produced recognized improvements. The lowest scores appear in Stopping Distance (overall mean 7.1; effectiveness 70%) and Rudder Effectiveness (overall mean 7.3; effectiveness 75%) — hydrodynamic response parameters most directly impaired by sedimentation-induced shallow-water effects. The largest expert–graduate divergence occurs in Rudder Effectiveness (experts: 7.5; graduates: 7.2), Propulsion Efficiency (experts: 8.0; graduates: 7.4), and Stopping Distance (experts: 7.2; graduates: 7.1) — precisely the parameters where operational experience most differentiates expert perception from educational preparation.

Qualitative Findings with Participant Quotations

Theme 1 — Sedimentation Hydrodynamic Impacts: Operational Recognition vs. Educational Underdevelopment

Maritime professionals described sedimentation's hydrodynamic effects in experientially grounded, multi-parameter terms that graduates and lecturers did not replicate. One senior professional with 28 years of port operations experience stated:

> *"When you are coming into a silted approach at low water, everything changes at the same time — the ship gets heavier in the water because of the density change, the bottom is pushing water aside more than you expect, the helm feels sluggish. You learn this. You feel it. But you cannot learn to feel it from a textbook or even from a simulator that does not model sediment properly. The graduates who come aboard for the first time in these conditions are always surprised. They know the theory but not the physics."*

Graduates confirmed this description from the receiving end:

> *"We studied shallow-water effects in our navigation courses — squat, bank suction, the interaction effects. I could explain them in an exam. But my first weeks working in the port approach in Makassar, I kept underestimating how much I needed to widen my track and slow down earlier. The channel is silted beyond what the charts show, and nobody had prepared me for that."*

Theme 2 — Navigation Aid Reliability: Acknowledged Improvements and Persistent Failure Modes

Chart accuracy received the highest score across all groups (overall mean 8.4), reflecting recognized improvements in electronic chart systems. However, participants across all groups identified persistent failure modes that reduced effective reliability below this headline score. One lecturer with 12 years of maritime navigation instruction noted:

> *"We teach students to trust ECDIS, and in most conditions that trust is justified. But we do not teach them systematically that in silted port approaches, the chart may be six to eighteen months behind the actual seabed. Survey cycles are slow in Indonesia. Students graduate trusting the chart absolutely, and then they find out the hard way that the chart shows two meters more depth than the sounder does."*

Theme 3 — Education–Industry Competency Gap in Sedimentation Risk

The education–industry gap in sedimentation risk competency was most visible in the Propulsion Efficiency and Rudder Effectiveness scores, where professional-graduate divergence was largest, and in graduates' qualitative accounts of transition difficulties. Three of the 13 graduates described encountering sedimentation conditions beyond their training, confirming Theme 1's pattern. Lecturers acknowledged the gap while attributing it to structural constraints:

> *"The curriculum mandates what topics we cover, and sedimentation effects on maneuverability are not listed as a required competency in the STCW framework. We address it briefly in nautical science, but we cannot simulate it, and there is no simulator available that models sediment-induced squat and resistance changes realistically. We work with what we have."*

Theme 4 — Technological and Governance Solutions: Consensus and Divergence

Real-time sedimentation monitoring and predictive modeling achieved the strongest convergent endorsement across all three stakeholder groups as the most impactful technological interventions. Experts, lecturers, and graduates all endorsed these approaches, though with different emphasis: experts focused on operational decision support, lecturers on curriculum integration potential, and graduates on the gap between their education and available technology. One professional described the operational case:

> *"If we had real-time depth data at the approaches — updated every tide cycle, not every survey cycle — we could give pilots and officers an actual picture of the current seabed, not a historical one. The technology exists. The governance and funding frameworks to deploy it consistently in Indonesian ports do not yet."*

Discussion

Mapping Findings to Research Questions

The cross-group results and qualitative themes collectively address all three research questions. **RQ1** (hydrodynamic impacts of sedimentation) is answered by the score differentials in Table 1 and Theme 1: Stopping Distance (effectiveness 70%) and Rudder Effectiveness (effectiveness 75%) are the most critically underprepared hydrodynamic competencies, with expert–graduate score gaps reflecting experiential knowledge that vocational education does not currently transmit. **RQ2** (navigation aid reliability) is addressed by the Chart Accuracy high scores and Theme 2: navigational technology has improved, but the survey cycle lag in Indonesian silted port approaches systematically overstates operational chart accuracy. **RQ3** (educational implications and curriculum reform) is addressed by Themes 3 and 4: the structural absence of sedimentation risk management from STCW-mandated curriculum frameworks, combined with simulator infrastructure gaps, constitutes the institutional mechanism producing the education–industry gap documented in Themes 1 and 2.

The Hydrodynamic Competency Gap: Theoretical Interpretation

The pattern in which stopping distance and rudder effectiveness receive the lowest scores across all groups — and where the expert–graduate divergence is largest — points to a specific theoretical explanation. These parameters are the most experience-dependent of the nine indicators: their operational significance can only be fully internalized through embodied experience with vessels responding sluggishly in shallow-water conditions, not through procedural description or static chart-reading instruction. This interpretation extends Hattingh et al.'s (2022) finding that competency-based assessment systems in safety-critical vocational contexts cannot verify operational readiness that has not been developed through authentic experience. The present findings locate the specific experiential gap: it is in the proprioceptive and situational recognition dimensions of sedimentation risk — knowing when the ship is behaving differently from expectation, and diagnosing why — that educational preparation most consistently fails.

Ardiyanto et al.'s (2023) finding that contextual familiarity and repeated exposure to safety-relevant stimuli are essential for developing reliable safety comprehension reinforces this interpretation. Graduates who have not been systematically exposed to sedimentationmodified maneuvering environments cannot develop the pattern-recognition baseline that expert professionals describe as "feeling the physics." The graduate quotation — "I could explain them in an exam. But... I kept underestimating how much I needed to widen my track" — is a precise experiential account of the gap between declarative knowledge and operational embodied competence that Ardiyanto et al.'s comprehension-compliance distinction theorizes.

Chart Accuracy's High Score: Not a Contradiction

The high scores for Chart Accuracy (expert mean 8.9; overall 8.4) might appear to contradict Theme 2's identification of survey cycle lag as a persistent failure mode. The resolution of this apparent contradiction is theoretically important. experts rate chart accuracy highly because they have developed operational strategies for managing chart uncertainty — treating published soundings as historical approximations requiring sonar cross-verification in silted areas. Lecturers rate it similarly because they teach chart systems whose formal accuracy has improved with ECDIS technology. Graduates rate it similarly because they trust chart systems they have been trained to use. None of these ratings captures the operational reality that Theme 2's qualitative data reveals: that in Indonesian silted port approaches, chart data may lag current conditions by 6 to 18 months — a gap that the rating instrument does not elicit from groups who have not operationally encountered the gap's consequences. This divergence between quantitative ratings and qualitative accounts is itself a methodological finding: Likert-scale ratings of perceived effectiveness aggregate across different operational contexts, and may overstate accuracy in specific high-risk domains where contextual knowledge differentiates expert from graduate assessment.

Zheng et al.'s (2025) PSILF framework explains this pattern as a "knowledge loss point" — the point where safety knowledge is present in formal systems (the chart) but is degraded in transmission to operational application (the actual seabed condition). The present study identifies the Indonesian port hydrographic survey cycle as precisely such a loss point in the sedimentation risk domain.

Structural Causes of the Education–Industry Gap

The lecturer quotation describing STCW non-mandate as the reason for limited sedimentation curriculum coverage identifies the same structural mechanism that Nidhom et al. (2025) document as the systemic barrier to vocational educator professional development: institutional performance evaluation frameworks that measure curriculum quality through regulatory compliance rather than graduate operational readiness. When maritime educators are accountable for STCW coverage compliance but not for graduates' hydrodynamic competency in sedimentation-affected operations, the institutional incentive structure produces exactly the gap Table 1 documents. Wahyudi et al. (2025) established that substantive university–industry partnership — specifically, industry engagement in curriculum content rather than in formal advisory committee structures — is the variable that closes this type of gap. The practical prescription for maritime polytechnics is therefore not merely content addition but governance restructuring: establishing industry accountability for sedimentation-specific curriculum content in the same way that STCW establishes regulatory accountability for general operational competencies. Aminah et al. (2025), demonstrating that formal outcome-based curriculum alignment frameworks can maintain systematic correspondence between program outcomes and course-level objectives, provide a methodological model for how sedimentation risk management could be inscribed as a formally tracked competency outcome without requiring STCW framework revision.

Implications for Maritime Education

Three specific curriculum interventions are indicated by the findings. First, simulator-based shallow-water maneuvering exercises under sedimentation conditions should be developed as a distinct instructional module, addressing the embodied competency gap identified in Themes 1 and 3. Simulator investment for this purpose is substantiated by the professional consensus that experiential exposure — not additional theoretical instruction — is the intervention required. Second, chart accuracy training should be redesigned to include systematic uncertainty management — teaching graduates to treat published soundings in high-sedimentation approaches as historical approximations and to apply sonar cross-verification protocols, rather than training chart-reading as a high-fidelity representation skill. Third, real-time sedimentation monitoring data should be integrated into maritime education infrastructure: as these systems become operationally available in Indonesian ports, familiarity with their interpretation and integration into passage planning should become a curriculum component. Othman et al. (2025), reviewing digitalisation in TVET, confirmed that effective technology integration requires coordinated investment in faculty capacity alongside equipment — meaning that the simulator and monitoring technology interventions require parallel lecturer professional development programs.

CONCLUSION

This study provides systematic multi-stakeholder evidence that sedimentation and navigation aid deficiencies in Indonesian maritime operations create a measurable education–industry gap most acutely in the hydrodynamic competency domains of stopping distance management (effectiveness 70%) and rudder effectiveness (effectiveness 75%) — the parameters where sedimentation-induced shallow-water effects most directly impair vessel response, and where operational experience most differentiates expert from graduate assessment. Chart Accuracy received the highest scores (overall mean 8.4; effectiveness 92%), reflecting recognized improvements in electronic navigation systems, but qualitative evidence establishes that survey cycle lag in silted Indonesian port approaches systematically overstates effective chart accuracy — a discrepancy that graduates have not been prepared to recognize or operationally manage.

The study contributes three evidence-grounded conclusions. First, the structural absence of sedimentation risk management from STCW-mandated curriculum frameworks — identified by lecturers as the institutional mechanism constraining coverage — constitutes a systemic safety education failure that maritime certification authorities should address by inscribing hydrodynamic sedimentation competency as a formally tracked outcome alongside existing operational standards. Second, real-time sedimentation monitoring systems and predictive modeling technologies represent the technological interventions with broadest stakeholder consensus and the most direct potential to close the operational information gap between current chart data and actual seabed conditions in Indonesian port approaches. Third, closing the education–industry gap in sedimentation risk competency requires simulator-based shallow-water maneuvering instruction — providing the embodied experience that the expert–graduate score differentials identify as the primary missing educational element — alongside the chart uncertainty management training and technology integration curricula that the findings specify.

Future research should evaluate the impact of simulator-based sedimentation maneuvering instruction on graduate operational competency through quasi-experimental designs, and should develop a risk-based sedimentation curriculum model that can be formally integrated into Indonesian maritime polytechnic standards within the existing STCW framework.

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