



# Design Verification of a Hybrid Wave-Damping System for Sustainable and Multi-Hazard-Resilient Port Infrastructure at Merak Port (Berth VII), Indonesia

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**Abstract:** Merak Port Berth VII is exposed to wave action, seismic loading, and soft-soil conditions, while retrofit works must be planned under limited marine access and a constrained schedule. This study verifies a hybrid wave-damping system comprising a platform-mounted wavescreen and a causeway revetment to improve multi-hazard resilience. Wind data from 2010–2022 were used for wave hindcasting to derive return-period wave conditions, while seismic actions and structural checks were evaluated using Indonesian and international port design criteria. Platform performance was assessed at the ultimate and serviceability limit states, and revetment stability was analyzed using the Morgenstern–Price method. Under the 500-year design combination, the platform satisfied strength and serviceability requirements, with vertical bearing safety factors of 3.40 and 3.53 based on SNI and UFC combinations, respectively, and deformations within operational limits. The revetment achieved a factor of safety of 1.49 under the same demand but became inadequate under the 1,000-year scenario, indicating the need for strengthening when higher reliability is required. The estimated construction cost is IDR 132,205,000,000, with an estimated duration of approximately 216 working days. This verification framework is transferable to brownfield Indonesian ports exposed to combined coastal and seismic hazards.

**Keywords:** Merak port; Multi-Hazard resilience; Seismic detailing; Slope stability analysis; Wave damping structures

## Introduction

Ports are strategic economic gateways that support trade, employment, and regional competitiveness. The quality and reliability of port infrastructure strongly influence logistics performance, seaborne trade, and broader economic growth, while sustainable port development increasingly depends on infrastructure that remains functional under environmental and operational stresses (Alamouh et al., 2021; Munim & Schramm, 2018; Verschuur et al., 2022). In archipelagic countries such as Indonesia, where maritime connectivity is essential, protecting port assets against coastal disruption is therefore not only a technical

requirement but also an economic and sustainability imperative. Recent Indonesian evidence further shows that hydrometeorological disturbances and port-area environmental risks can directly affect operations and coastal management priorities (Rahili et al., 2023; Yusrizal et al., 2024).

Merak Port, located along the Sunda Strait, operates in a demanding multi-hazard environment characterized by energetic wind-generated waves, tide-modulated pore-water conditions, high regional seismicity, and soft subsoil (Rehman et al., 2024; Su et al., 2021). These conditions make resilience-oriented retrofit especially important for Berth VII, where structural inadequacy or prolonged downtime would directly

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affect operational continuity (Verschuur et al., 2022). The challenge is further intensified by brownfield constraints, including limited marine access and a restricted construction window. Under such conditions, engineering decisions must address not only ultimate strength but also serviceability, constructability, cost, and implementation time (Alamouh et al., 2021).

Existing design practice commonly evaluates hydrodynamic loading, structural response, and geotechnical stability as separate tasks. For active port retrofits, however, this fragmented approach can obscure the governing failure mechanism and underrepresent the operational significance of deformation. In addition, technical verification is often presented without a clear linkage to implementation planning, even though such linkage is critical for investment decisions at operating ports. Recent studies have advanced the seismic assessment of pile-supported wharves and the reliability evaluation of coastal structures under extreme wave conditions (Radfar & Galiatsatou, 2023; Rehman et al., 2024; Su et al., 2021). Nevertheless, integrated studies that combine wave hindcasting, structural verification, revetment stability, and implementation planning within a single retrofit-oriented framework for brownfield ports on soft ground remain limited.

Accordingly, this study develops an integrated verification framework for Berth VII at Merak Port. Seismic site classification and hazard characterization follow SNI 1726:2019, while the response of bridge- and marine-type components is cross-checked against SNI 2833:2016, UFC 4-152-01, and Port of Long Beach wharf criteria. This combined use of standards is intended to distinguish general seismic hazard characterization from component-level verification relevant to port infrastructure, consistent with recent studies that emphasize both system-level and component-level seismic assessment for port facilities (Fotopoulou et al., 2022; Özcebe et al., 2022). Pseudo-static seismic verification uses coefficients  $k_h$  and  $k_v$ , and revetment stability is assessed against a seismic target of  $FS \geq 1.10$ , in line with recent probabilistic work showing that the choice and uncertainty of seismic coefficients materially affect pseudo-static slope-stability results (Li et al., 2021). Wave conditions are derived from sectoral wind-to-wave hindcasting, allowing environmental forcing, structural response, and geotechnical performance to be evaluated within one consistent framework.

The novelty of this study lies in three aspects. First, it integrates wave hindcasting, seismic verification, platform ultimate and serviceability checks, and causeway revetment slope stability into a single workflow for a brownfield port asset founded on soft ground. Second, it explicitly elevates serviceability and operational performance to the same decision level as

strength and stability, recognizing that relatively small displacements may still disrupt berth functionality. Third, it links technical verification to a costed implementation plan and indicative construction schedule, thereby supporting investment and phasing decisions rather than design review alone. Therefore, this study aims to characterize the wave-seismic design environment of Berth VII, verify the performance of a platform-mounted wavescreen and causeway revetment under combined hazards, and develop a replicable verification framework for Indonesian ports exposed to both coastal and seismic risk.

## Method

### *Study Area and Data Used*

The study focuses on Berth VII (Dermaga VII) at Merak Port, Banten, Indonesia. Secondary datasets comprise factual geotechnical investigation reports (2017), analytical design files for the causeway (2018) and platform (2018), as-built drawings for Berth VII design-build works (2019), and design review and strengthening reports for the causeway and platform (2022). Wind observations (2010–2022) were compiled to derive directional statistics and extremes for wave hindcasting (Rahili et al., 2023). To improve traceability, all documents were catalogued with version control and metadata (date, originator, coordinate reference, and vertical datum), consistent with established data-stewardship principles for making engineering datasets more findable, reusable, and auditable (Wilkinson et al., 2016). Consistency checks compared as-built geometries against design elevations to identify deviations relevant to hydrodynamic loading (e.g., crest levels and toe elevations), following the same logic used in digital scan-versus-model verification for construction geometry control (Bariczová et al., 2021). Data entry followed a double-entry protocol; outliers in wind records were screened using the interquartile range and cross-checked against adjacent stations or periods where available, in line with recent quality-control practice for wind observations before downstream analysis (Lu et al., 2024). Where drawings conflicted, priority was given to signed as-built documents, and all assumptions were logged for sensitivity testing.

### *Design Basis and Codes*

Return-period criteria adopt a 100-year wave and 500-year seismic event, consistent with risk-informed design guidance for high-value coastal assets and long-service-life revetment systems (Elkersh et al., 2023). Structural and load provisions draw on ACI 357, BS 6349-2:2010, SNI 1726:2019, SNI 2847:2019, SNI 2833:2016, the Port of Long Beach Wharf Design Criteria, and UFC criteria for piers and wharves. Verification

follows limit-state principles, checking the Ultimate Limit State (ULS) for strength and stability and the Serviceability Limit State (SLS) for deformation, crack control, and vibration, in line with recent reviews showing that displacement and damage control are central to modern code-based seismic verification (Pavel & Vacareanu, 2023). Performance targets adopt operational functionality for berth use, life safety under the design earthquake, and damage control consistent with code-based ductility and detailing requirements. Load, resistance, importance, and partial safety factors were taken directly from the cited standards, with local calibration permitted where Indonesian practice allows; this approach is also consistent with recent displacement-based wharf design studies that relate seismic hazard levels to explicit structural performance targets (Gao et al., 2024).

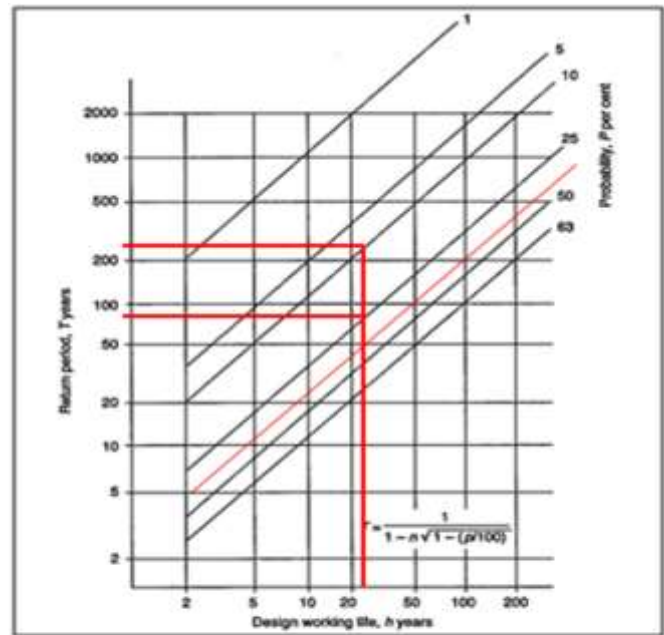
*Environmental Forcing and Wave Hindcasting*

Wind records (2010–2022) were processed to compute daily maxima and directional means and to construct wind-rose visualizations and frequency tables. Wave conditions were then hindcast from the wind field using empirical coastal-engineering relationships and tabulated methods, with fetch lengths estimated along dominant sectors, which is consistent with recent work showing that wind quality, directional exposure, and fetch limitation strongly control hindcast wave accuracy in coastal basins (Bujak et al., 2023; Morim et al., 2022). Design-wave selection followed the Port Designer’s Handbook, ensuring consistency between wave statistics and return periods; the relationship between structural design life, return period, and exceedance probability underpinning this selection is schematized in Figure 1.

Figure 1a formalizes the probabilistic basis of design by linking the target annual exceedance probability to the selected return period for a specified design working life, thereby providing a transparent rationale for aligning risk tolerance with the facility’s intended service duration. In parallel, the companion classification matrix (Figure 1b) operationalizes this concept by mapping function category and design working life (temporary, interim, or long-term) to recommended minimum return periods; thus, higher-consequence assets are assigned longer return periods to reduce the likelihood of exceedance over their service life, consistent with recent multivariate return-period analyses for coastal-structure design (Orcel et al., 2021).

Consistent with these criteria, Port VII Merak, characterized by high economic value and potentially elevated operational consequences, should be designed using at least a 100-year significant wave-height return period as a defensible lower bound, while a structured optimization can be undertaken to refine the selected

return period toward an optimum design solution without compromising reliability. The resulting significant wave height and characteristic period defined wave loads for the platform berth pocket and revetment toe. Finite-depth corrections and shallow-water transformations (shoaling and refraction) were applied where depth-to-wavelength ratios warranted. Near-structure kinematics used linear wave theory in accordance with BS 6349-2:2010, with breaking-limit checks to avoid unrealistically large crest elevations. Directional spreading was represented through sectoral analyses to capture berth-aligned transmission into the pocket, which is consistent with recent studies emphasizing the importance of frequency-direction wave characterization and coastal-to-nearshore wave transformation for engineering-scale applications (Brus et al., 2021; Mazzaretto & Menendez, 2024). Assumptions related to sea-level reference and tidal range for extreme combinations were recorded for sensitivity analyses (Radfar & Galiatsatou, 2023).



Function Category	Category Description	Design Working Life (Years)		
		5 or less (Temporary)	20 (Interim)	50 (Long-term)
1	Structures presenting a low degree of hazard to life or property	5	20	50
2	Normal structures	20	50	100
3	High property value or high risk to people	50	100	100

**Figure 1.** Relationship between structural design life, return period, and wave exceedance probability (schematic)

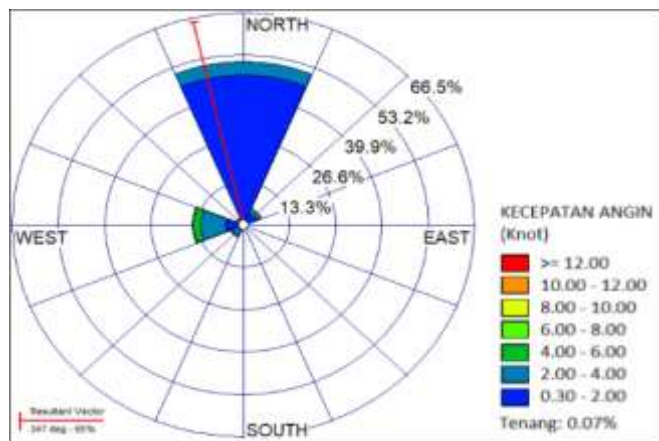
*Seismic Hazard Characterization*

Site class was classified as SE (soft soil) from average NSPT values in accordance with SNI 1726:2019, consistent with studies showing that soft-soil conditions can significantly amplify seismic response (Peng et al., 2024). Regional hazard parameters were taken from the 2017/2019 national maps and used with pseudo-static

coefficients for slope-stability checks, as commonly applied in Indonesian practice and supported by recent probabilistic analyses of seismic-coefficient effects (Li et al., 2021). Structural verification used a 5%-damping elastic response spectrum for initial sizing and equivalent static actions for applicable components. Vertical seismic effects, soft-soil amplification, and near-fault directivity were also considered in the load combinations (González-Cao et al., 2019; Xie et al., 2023).

*Structural Model for the Platform Wavescreen*

The wavescreen was idealized as a vertical barrier (e.g., CSP/sheet-pile with reinforced cap) supported by the platform foundation system. Load cases included self-weight, hydrostatic and hydrodynamic wave, and inertia effects from the design-level earthquake. Two load-combination families were evaluated: SNI-based combinations per SNI 1726:2019 and SNI 2847:2019, and UFC-based combinations per UFC/POLB WDC (Rehman et al., 2024; Su et al., 2021). Material properties and detailing limits were in accordance with ACI 357 and SNI 2847:2019, with checks for strength and serviceability, including displacement limits within berth operational tolerances. Boundary conditions reflected realistic connectivity between the wavescreen cap and the platform system. Soil-structure interaction was represented using subgrade reaction springs consistent with interpreted stiffness from geotechnical data (J. Wang et al., 2023).



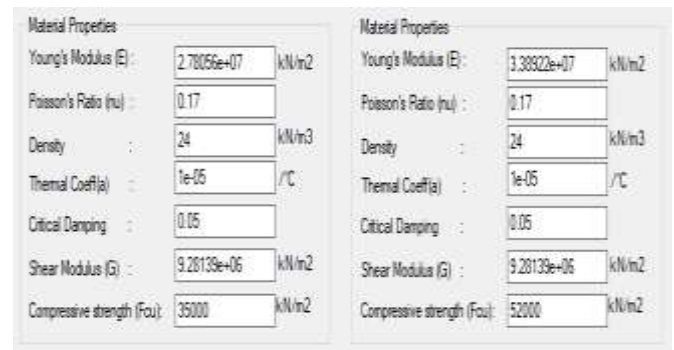
**Figure 2.** Dominant wind rose diagram (2010–2022) highlighting N-W sectors

*Slope Stability Analysis for the Causeway Revetment*

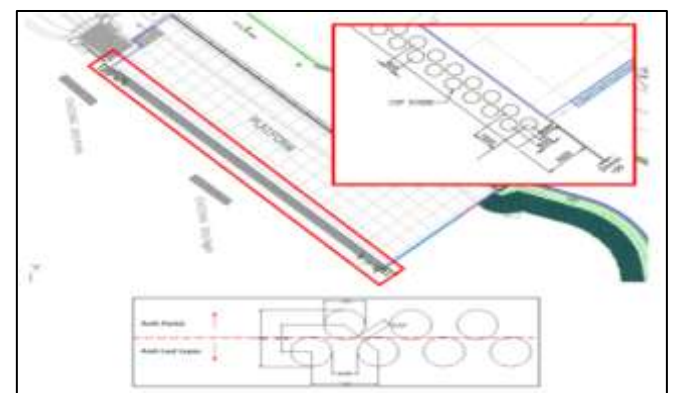
Stability of the revetment embankment was evaluated using the Limit Equilibrium Method with the Morgenstern–Price formulation. Geometries reflected as-built profiles, and soil parameters were interpreted from BH-08 and adjacent borings. Analyses considered static water level, design wave run-up effects, and pseudo-static seismic loading using coefficients  $k_h$  and  $k_v$ , consistent with recent studies showing that seismic-

coefficient selection materially affects slope-stability predictions (Li et al., 2021). The target factor of safety was  $FS \geq 1.10$  under seismic conditions per SNI 8460:2017.

Drawdown and transient pore-pressure influences were bracketed by steady-state and rapid-drawdown envelopes to reflect tidal modulation, which is consistent with recent findings that drawdown can significantly reduce slope stability through adverse seepage and pore-pressure redistribution (Pandey et al., 2023). Sensitivity cases varied  $c$ ,  $\phi$ , and unit weight within documented ranges to quantify the robustness of the computed FS. For the platform system, vertical bearing capacity, settlement, and lateral displacement were computed under SNI and UFC combinations for the 500-year event and compared with operational limits, while soft-soil effects were considered in line with evidence that such ground conditions can amplify seismic response and deformation demand (Peng et al., 2024).



**Figure 3.** Material properties in the wavescreen structural model



**Figure 4.** Plan location and CSP pile arrangement for the wavescreen on the platform, and typical CSP (D1000) arrangement and spacing

*Cost Estimation and Implementation Schedule*

The Bill of Quantities (BoQ) was compiled from measured quantities for preparation works, platform strengthening/wavescreen works, and causeway revetment works. Unit rates referenced Provincial Regulation of Banten No. 39/2021 on Government

Goods/Services Standard Prices. The engineer's estimate totaled IDR 132,205,000,000 (approximately IDR 132.21 billion). The execution plan assumed 216 working days and was sequenced to accommodate marine access, tides, and safety constraints.

A risk register identified natural (extreme weather, high waves, and seismic), environmental (soft ground, sediment-related environmental exposure, and heavy-vehicle interference), managerial and financial, technical, and construction risks. Mitigation included method statements for rock placement and compaction, verification of revetment toe stability, and contingency for design adjustments during construction. QA/QC comprised conformance checks to drawings and specifications, material testing, and hold-point inspections at critical stages. One-at-a-time sensitivity analyses were performed on the principal inputs (wind extremes, fetch length, water level,  $c'/\phi'$  ranges, and subgrade stiffness). Response metrics included hindcast wave conditions at the berth pocket, revetment FS, and platform displacements (Yusrizal et al., 2024).

## Result and Discussion

### *Environmental Forcing and Design Wave Climate*

Wind statistics (2010–2022) indicate a strongly directional regime dominated by N (51.11%) and W (14.84%), with lesser contributions from NE (5.73%), SW (4.24%), and NW (2.45%) (Figure 2). This persistent northerly–westerly exposure, together with the available fetch, supports adoption of a  $\geq 100$ -year design wave for a high-value berth to keep exceedance risk within acceptable bounds over the asset life, consistent with recent multivariate return-period approaches for coastal-structure design (Orcel et al., 2021). Sectoral hindcasting ensures that berth-aligned transmission into the pocket is captured after finite-depth and shoaling/refraction adjustments per BS 6349-2:2010; these corrections govern the near-structure kinematics used for wavescreen and revetment loading and are consistent with recent studies on wave characterization and fetch-limited coastal modelling (Bujak et al., 2023; Morim et al., 2022). This interpretation is also consistent with recent Indonesian studies showing that tidal dynamics, wind forcing, and coastal flooding processes can directly affect port-area operations and coastal vulnerability, particularly in exposed coastal settings (Latifah et al., 2025; Rahili et al., 2023).

### *Platform Wavescreen Performance Strength and Serviceability*

For the 500-year seismic case, vertical bearing-capacity checks yield FS = 3.40 (SNI combinations) and FS = 3.53 (UFC combinations). Settlements remain 10.4–10.5 mm ( $< 25$  mm limit) and lateral displacements 23.0–

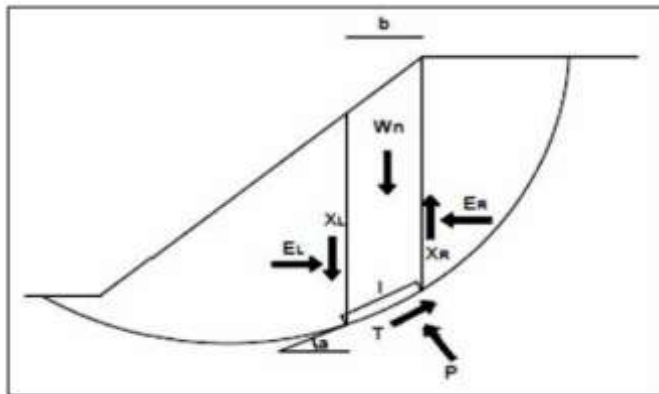
23.2 mm ( $< 100$  mm), all within operational tolerances. Under the 1,000-year seismic case, the platform still shows FS  $\geq 3.34$  with comparable deformations, indicating a healthy reserve. Cross-code agreement (SNI vs UFC/POLB WDC) suggests that the response is not an artefact of a single factor set, increasing confidence in the sizing and detailing. Operationally, displacements at the fender line are small relative to berth tolerances, implying minimal impact on mooring safety and cargo-handling clearances (Rehman et al., 2024). The results also suggest that corrosion-protection provisions (cover and exposure class) and crack-width control per SNI 2847:2019/ACI 357 are adequate to maintain durability under cyclic wetting and chloride ingress. This interpretation is in line with recent performance-based studies showing that pile-supported wharf systems can retain acceptable seismic response and serviceability when soil–pile interaction and hazard-level differentiation are properly represented (Rehman et al., 2024; Su et al., 2021).

The structural analysis results indicate that the maximum axial force  $F_x$  is 4707.76 kN. The maximum shear force in the y-direction  $F_y$  is 142.41 kN, while the maximum shear force in the z-direction  $F_z$  is 174.79 kN. For the torsional moment, the highest recorded value is  $M_x = 0.20$  kNm. In terms of bending moments, the maximum moment in the y-direction is  $M_y = 3206.00$  kNm, and the maximum moment in the z-direction is  $M_z = 2001.52$  kNm. These values represent the most critical load effects observed in the structure under the governing load cases, which is consistent with recent studies on pile-supported wharves that treat axial force, shear force, and bending moment as key engineering demand parameters in seismic performance assessment (Boyke & Nagao, 2022; Yun & Han, 2021). Reporting these actions in kN and kN m also provides a clearer and more internationally consistent basis for structural interpretation and comparison with recent wharf-response studies (Boyke & Nagao, 2023).

### *Revetment Slope Stability Under Combined Actions*

Limit-equilibrium analyses using the Morgenstern–Price method (BH-08 parameters; Figure 5) indicate FS = 1.49 for the 500-year event (pseudo-static  $k_h = 0.18$ ,  $k_v = 0.12$ ), comfortably above the FS  $\geq 1.10$  seismic target. For a 1,000-year scenario, the revetment fails to maintain equilibrium, with FS dropping well below 1.0, indicating global instability under the assumed parameter set. The sharp reduction in stability reflects the combined effects of soft subsoil (site class SE), elevated inertial demand, and possible effective-stress reduction near the armour toe during high water plus wave run-up, which is consistent with recent findings on seismic coefficient sensitivity, soft-soil amplification, and instability under drawdown or overflow conditions (Kim et al., 2023;

Peng et al., 2024). Practically, the current revetment concept is adequate up to the 500-year seismic demand and would require targeted strengthening, such as a toe key, improved underlayer/filter robustness, or local ground improvement, if higher reliability is mandated. This interpretation is also consistent with recent reliability-oriented assessments showing that relatively small changes in hydraulic and geotechnical assumptions can materially change the stability margin of embankment and coastal structures (Kim et al., 2023; Li et al., 2021).



**Figure 5.** Forces acting on slices along the critical slip surface in the revetment embankment (schematic)

*Sensitivity and Uncertainty*

Parametric sweeps on shear strength and unit weight confirm their first-order control on FS, while hydraulic sensitivity is governed by the selection of extreme water levels, which modifies pore-pressure boundary conditions at the toe (Li et al., 2021). For the platform, settlements were only modestly sensitive to the adopted subgrade modulus; maintaining conservative stiffness envelopes is therefore prudent where geotechnical data spacing is limited, because soil-foundation interaction can materially influence settlement and deformation patterns (Khosravifardshirazi et al., 2022). These findings justify conservative envelopes for design-governing combinations and post-construction monitoring at displacement hot spots to validate assumptions (Radfar & Galiatsatou, 2023). Seismically, the 500-year basis yields acceptable performance for both elements; however, the revetment response under the 1,000-year demand confirms that reliability targets must remain tied to asset criticality and lifecycle risk appetite, especially where settlement-related uncertainty and parameter variability remain significant (Zhou & Wang, 2025).

*Constructability, Cost, and Program*

The engineer’s estimate for permanent works is IDR 132,205,000,000 (approximately IDR 132.21 billion) with

an implementation duration of 216 working days (6 days/week, 7 h/day). This envelope is consistent with the project scope (platform/wavescreen and causeway works) and with the need to sequence marine operations around tides and safety constraints. Tying return-period choices to cost and schedule provides a transparent basis for budget-aware resilience planning and supports phased delivery if procurement constraints arise, which is consistent with findings that seaport resilience planning often leads to infrastructure-related enhancement strategies and implementation-oriented decision making (Kalaidjian et al., 2022). Operational risks (heavy-vehicle traffic and cargo-handling interference), technical risks (toe instability, insufficient compaction, and armour gradation), and managerial/financial risks were identified (Su et al., 2021).

This framing is also consistent with seaport-construction risk studies showing that adverse incidents can materially affect environmental performance and timely project completion (Kaup et al., 2022). Mitigation hinges on method statements for rock placement/compaction, strict underlayer or filter QA, and hold-point inspections at critical stages; similar wharf-construction studies likewise emphasize that construction safety and process control are critical to realizing intended performance in offshore work environments (Y. Wang et al., 2024). These controls are essential to achieve the computed safety margins, particularly for the revetment, where construction quality at the toe governs performance. In addition, recent port-area studies in Indonesia highlight that environmental risk management should also be treated as part of infrastructure resilience during implementation and operation (Yusrizal et al., 2024).

**Conclusion**

This study developed an integrated verification framework for a hybrid wave-damping system at Berth VII, Merak Port, by combining wind-to-wave hindcasting, code-consistent seismic actions, structural verification of a platform-mounted wavescreen, limit-equilibrium analysis of the causeway revetment, and cost-schedule appraisal. The results show that the platform satisfies both ULS and SLS requirements, with vertical bearing safety in the range of FS = 3.40–3.53 and deformations within operational limits. The revetment also satisfies the adopted 500-year seismic design basis, with FS = 1.49, but fails to meet safety requirements under the 1,000-year seismic check, indicating global instability and the need for strengthening if a higher reliability target is required. From a practical perspective, the findings support adoption of at least a 100-year wave design criterion with explicit seismic

verification for brownfield port infrastructure on soft ground. Strategic recommendations include maintaining the current design basis for near-term implementation and applying phased upgrading if the required reliability level increases. Technical recommendations include revetment strengthening through toe buttressing, improvement of underlayer and filter robustness, crest raising or armour regrading where needed, and local ground improvement or drainage enhancement in critical zones. The estimated construction cost of approximately IDR 132.21 billion and an implementation period of about 216 working days indicate that the proposed intervention is feasible under constrained marine access conditions. This study is limited by the use of hindcast wave data without in-situ measurements, simplified two-dimensional limit-equilibrium assumptions, and simplified treatment of joint extremes. Future research should incorporate field monitoring data, such as ADCP measurements, pore-pressure records, settlement observations, and deformation monitoring, to validate the design assumptions. Further studies are also recommended to apply coupled hydro-seismic and soil-structure interaction modelling, as well as probabilistic reliability and fragility analysis, to support staged upgrading toward higher performance targets.

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#### Author Contributions

Conceptualization, S.M. and R.D.L.; methodology, S.M. and M.A.S.; validation, S.M., U.A. and E.S.; formal analysis, S.M. and R.D.L.; investigation, S.M., and R.D.L.; resources, S.M., U.A. and E.S.; data curation, R.D.L. and R.T.U.; writing – original draft preparation, S.M., R.D.L., and R.T.U.; writing – review and editing, U.A., E.S., and M.A.S.; visualization, R.D.L. and R.T.U.; supervision, S.M., U.A., E.S., and M.A.S.; project administration, S.M. All authors have read and agreed to the published version of the manuscript.

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#### Conflicts of Interest

The authors declare no conflict of interest.

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