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OVERTOPPING RISK AND FREEBOARD ASSESSMENT OF THE SIRENJA BEACH POLDER UNDER A 100-YEAR SEA LEVEL RISE SCENARIO

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Abstract

Coastal polders built as post-disaster protection structures face a long-term design question that field performance alone cannot answer: how much freeboard margin will remain once projected sea level rise is added to present-day tidal extremes, and at what point does that margin become a structural risk rather than a design comfort factor? This study addresses that question for the Sirenja Beach polder, Donggala Regency, Central Sulawesi, a rubble-stone embankment (crest elevation 4.67 m) constructed after the 2018 earthquake and tsunami. Using 100-year sea level rise projections consistent with IPCC AR6 scenarios and hydrodynamic water-level output generated in a companion Delft3D modeling study, this paper develops a freeboard-based risk classification framework and applies it to compare present-day and future overtopping risk at the site. Maximum water level rose from 1.17 m under present tidal conditions to 2.17 m under the 100-year projection, reducing the available freeboard from 3.50 m to 2.50 m, a reduction of approximately 29%. Applying a four-tier risk classification (Low, Moderate, High, Critical) benchmarked against regional dike and coastal-defense freeboard guidance, the Sirenja polder remains in the Low-risk category under both scenarios, but the trend indicates that continued sea level rise beyond the 100-year projection, or additional land subsidence, could shift the structure into the Moderate-risk category within a shorter timeframe than the design horizon assumes. The findings support a monitoring-triggered adaptation approach rather than immediate structural intervention, and the proposed freeboard classification framework offers a transferable, low-data screening tool for other post-disaster coastal structures in tsunami-affected regions of Indonesia.

Keywords: coastal adaptation; freeboard; overtopping risk; polder; sea level rise

1. Introduction

Coastal protection structures built in the aftermath of a disaster are typically designed to address the hazard that triggered their construction, yet they must also perform under conditions that will only materialize decades later. This tension is particularly acute for polders and embankments built after tsunami events, where the immediate design driver is tidal-flood and inundation control, while the structure's design life inevitably overlaps with the timeframe over which global sea level rise is projected to accelerate (IPCC, 2021; Nicholls and Cazenave, 2010). A structure judged adequate against present-day tidal extremes may carry a materially different risk profile once realistic sea level rise allowances are added, yet this forward-looking freeboard question is often left implicit in post-disaster reconstruction projects rather than assessed quantitatively (Nicholls et al., 2021).

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The Sirenja Beach polder in Donggala Regency, Central Sulawesi, illustrates this situation directly. The structure was built following the 28 September 2018 Sulawesi earthquake and tsunami, which caused coastal morphological change and land-elevation shifts along the Central Sulawesi coastline (Pakoksung et al., 2019; Chaussard et al., 2013). The polder's rubble-stone embankment, with a crest elevation of 4.67 m, was designed primarily to control tidal inundation and manage land drainage in the affected village of Tompe (Ministry of Public Works and Housing, 2020). Its performance against present-day tidal dynamics has been characterized in a companion hydrodynamic modeling study using Delft3D, but that evaluation, like most post-construction assessments, centers on current conditions rather than on how much protective margin remains once long-term sea level rise is factored in.

Globally, freeboard and overtopping-risk frameworks are well established in dike and coastal-defense engineering, most notably through the EurOtop overtopping manual and related wave-overtopping formulations (Pullen et al., 2007; Burcharth and Hughes, 2011), and have been applied to assess adaptation needs for deltaic and low-lying coasts in the Netherlands and Vietnam's Mekong Delta (Stive et al., 2020; Tri et al., 2019). In Indonesia, similar freeboard-based reasoning has informed adaptation planning in subsiding urban coastlines such as Jakarta and Semarang (Abidin et al., 2015; Wilson et al., 2021), and in tidal-flood-prone polder systems in Demak (Mustaqim et al., 2022). However, this type of forward-looking freeboard classification has rarely been applied to small, post-disaster rural polders in eastern Indonesia, where reconstruction is typically driven by immediate hazard response rather than long-horizon climate risk screening (Amar et al., 2024).

This study addresses that gap by developing a freeboard-based overtopping-risk classification for the Sirenja Beach polder and applying it to compare present-day and 100-year sea level rise conditions. Rather than re-deriving the hydrodynamic simulation reported in the companion modeling study, this paper uses the resulting water-level outputs as an input to a risk-screening framework benchmarked against established freeboard guidance, with the aim of translating hydrodynamic model output into a form directly usable by infrastructure planners for adaptation-timing decisions.

2. Method

2.1 Study Area and Structure Characteristics

The assessment covers the Sirenja Beach polder, Tompe Village, Sirenja District, Donggala Regency, Central Sulawesi (0°12'36.04" S, 119°48'28.95" E). The embankment is approximately 1.64 km long, constructed from stacked rubble stone, with a surveyed crest elevation of 4.67 m above mean sea level (MSL).

2.2 Water-Level Inputs

Maximum water levels used in this assessment were obtained from a two-dimensional Delft3D-FLOW/WAVE hydrodynamic model of the Sirenja coastal domain, reported in full in a companion validation study, where the model was calibrated against a 15-day field tidal record (RMSE = 0.048 m, MAE = 0.031 m). Two water-level outputs from that model were used here:

(i) The present-day post-construction condition, and

(ii) A 100-year sea level rise projection obtained by adding a 1 m water-level allowance to the open-boundary condition, consistent with IPCC AR6 high-emissions long-term projections.

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This paper does not repeat the wind, wave-hindcasting, or grid-configuration details of the underlying model; readers requiring the full hydrodynamic development are referred to that companion study.

2.3 Freeboard and Risk Classification Framework

Freeboard (Fb) was defined as the vertical margin between the polder crest elevation (Ec) and the maximum simulated water level (WLmax) for a given scenario: Fb = Ec - WLmax. This definition follows standard dike-safety practice in which freeboard represents the buffer available to absorb wave run-up and short-term surge before overtopping occurs (Pullen et al., 2007; Burcharth and Hughes, 2011). Because detailed wave run-up data specific to the Sirenja site were not available at the resolution required for a full EurOtop-type overtopping-discharge calculation, this study applied a simplified four-tier freeboard classification adapted from regional dike-safety and coastal-adaptation guidance (Stive et al., 2020; Wilson et al., 2021): Low risk (Fb > 2.0 m), Moderate risk (1.0-2.0 m), High risk (0-1.0 m), and Critical risk (Fb < 0, i.e., the crest is submerged). This classification was applied to both the present-day and 100-year sea level rise water-level outputs to evaluate how the risk category shifts over the projected timeframe.

3. Results and Discussion

3.1 Water-Level Change Under Sea Level Rise

Hydrodynamic simulations reveal that the peak water surface elevation within the polder system escalates from 1.17 m under the current post-construction baseline to 2.17 m when subjected to a 100-year sea-level rise (SLR) projection. This deterministic increment of 1.0 m aligns precisely with the prescribed boundary-condition allowances for future climate scenarios. Consequently, this amplification in water level precipitates a direct and critical reduction in the available freeboard, which degrades from an initial 3.50 m to 2.50 m. Such a reduction represents an approximate 29% attenuation of the present-day safety margin, highlighting potential vulnerabilities in the flood defense infrastructure. A comprehensive visual juxtaposition of these scenarios is provided in Figure 1, which delineates the static polder crest elevation against the maximum hydrodynamic water levels, thereby explicitly quantifying the residual freeboard for both current and projected climate conditions

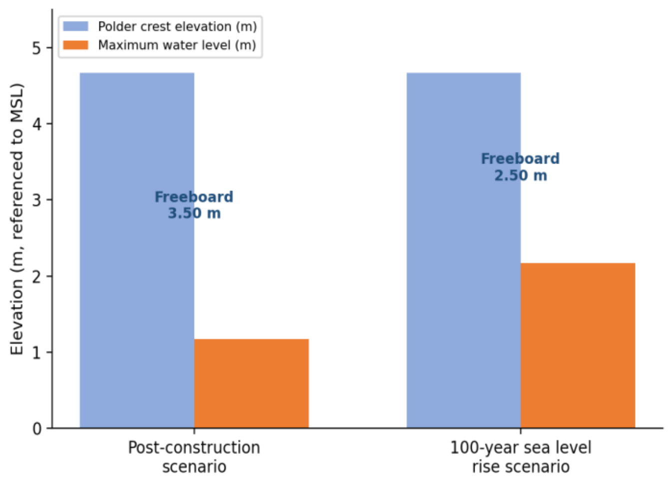

Figure 1. Comparison of polder crest elevation, maximum water level, and resulting freeboard margin under present-day and 100-year sea level rise scenarios

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Despite the substantial relative attenuation of the freeboard, the absolute residual freeboard of 2.50 m under the 100-year SLR scenario significantly exceeds the statutory minimum thresholds prescribed by regional dike-safety guidelines for comparable rural coastal embankments (Stive et al., 2020; Wilson et al., 2021). This structural resilience implies that the crest elevation of the Sirenja polder, evidently configured with a highly conservative safety factor during the post-tsunami reconstruction phase, inherently affords enhanced long-term adaptive capacity. Consequently, the infrastructure exhibits a robust climate tolerance that far surpasses the performance of conventional structures dimensioned exclusively for contemporary hydrodynamic boundary conditions and tidal extremes

3.2 Risk Classification Outcome

Evaluation of the polder’s vulnerability, executed through the predefined four-tier freeboard classification matrix, demonstrates a remarkable consistency in operational safety across varying temporal scenarios. As delineated in Table 1, the simulated residual freeboards—spanning from 3.50 m under contemporary conditions to 2.50 m under the 100-year SLR scenario—consistently satisfy the stringent criteria for the 'Low-risk' tier. It is imperative to highlight that the anticipated climatic anomalies examined in this study preclude any paradigm shift in the infrastructure's vulnerability, entirely circumventing the 'Moderate', 'High', and 'Critical' categories. From a coastal and hydraulic engineering perspective, the persistence of this low-risk status rigorously validates the efficacy of the initial infrastructure dimensioning. The continuous provision of a substantial freeboard buffer ensures that the structural integrity remains uncompromised, guaranteeing uninterrupted flood mitigation functionality without the immediate requisite for major adaptive structural interventions.

Table 1. Freeboard-based overtopping risk classification and outcome for the Sirenja Beach polder

Risk Class	Freeboard Margin	Expected Impact	Recommended Action
Low	> 2.0 m	Minimal	Routine inspection
Moderate	1.0 - 2.0 m	Possible splash-over in extreme events	Periodic monitoring; maintain crest condition
High	0 - 1.0 m	Frequent wave overtopping likely	Consider crest heightening or wave wall
Critical	< 0 m (submerged)	Structural failure / inundation likely	Urgent redesign required

Despite the current structural reliability, this outcome should in no way imply that the overtopping threat for the Sirenja Beach coastal defense system is permanently neutralized. The explicit 29% reduction in available freeboard over the modeled century delineates a clear and progressive trajectory of increasing hydrodynamic vulnerability. Furthermore, the stability of this classification is inherently contingent upon two critical, yet highly variable, parameters not fully assimilated into the present hydrodynamic framework: (i) extreme sea-level rise scenarios driven by upper-bound emissions pathways beyond the 100-year horizon, and (ii) aggressive localized land subsidence. As extensively documented in coastal areas of Indonesia experiencing significant tectonic deformations and aquifer depletion, subsidence can severely compound the effects of global mean sea-level rise (Chaussard et al., 2013; Abidin et al., 2015).

Should either of these exacerbating environmental stressors—or their synergistic amplification—induce an additional freeboard compression of 1.0 to 1.5 m beyond the established century-scale projections, the infrastructure’s vulnerability classification will be precipitously downgraded into the 'Moderate-risk' domain. Breaching this critical operational threshold implies that the embankment

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would no longer possess sufficient reserve capacity to dissipate energy from secondary hydrodynamic forcings, such as extreme wave run-up or coincident storm surges. At this critical juncture, conventional passive risk management paradigms—primarily consisting of periodic topographical surveillance, visual inspections, and localized maintenance—will be rendered fundamentally obsolete. To mitigate the escalated probability of catastrophic overtopping and subsequent hinterland inundation, it becomes imperative to transition toward the immediate execution of major adaptive structural upgrades. Such proactive interventions would likely necessitate physical crest elevation augmentation, the retrofitting of wave-deflecting parapet walls, or comprehensive structural toe reinforcement to withstand altered hydrostatic and hydrodynamic pressures, thereby dynamically restoring the essential hydraulic safety margins.

3.3 Comparison with Other Indonesian and Regional Cases

The residual freeboard margin identified for the Sirenja polder exhibits a substantially greater buffer capacity when compared to severely compromised embankment systems documented in Semarang and Demak. In those northern Java locations, the synergistic effects of aggressive, aquifer-depletion-induced land subsidence and relative sea-level rise have rapidly attenuated effective freeboards to sub-meter thresholds, thereby precipitating a critical downgrade of those structures into the 'High-risk' domain under an equivalent vulnerability framework (Wilson et al., 2021; Mustaqim et al., 2022). This stark regional dichotomy highlights a crucial infrastructural outcome: the post-disaster reconstruction phase in Central Sulawesi—operating within a distinct geological setting characterized by comparatively subdued continuous subsidence rates relative to Java's hyper-subsiding unconfined aquifers—has yielded a defense structure with significantly enhanced long-term structural resilience. Furthermore, this comparative insight suggests that the freeboard vulnerability matrix applied herein possesses significant potential as a robust, rapid-appraisal diagnostic framework. Extending this screening methodology across diverse post-disaster coastal infrastructures in the tectonically complex regions of eastern Indonesia would critically optimize the strategic prioritization of adaptive engineering interventions, decisively directing capital resources toward specific coastal zones where hydro-isostatic and climatic stressors compound most aggressively.

3.4 Adaptation Implications

Predicated upon the persistent 'Low-risk' categorization across all simulated deterministic scenarios, the current hydrodynamic assessment precludes the immediate necessity for capital-intensive structural interventions, such as crest elevation augmentation, at the Sirenja Beach polder system. Conversely, the empirical findings strongly advocate for the implementation of a monitoring-triggered Dynamic Adaptive Policy Pathway (DAPP). This strategic management framework necessitates high-resolution, periodic geodetic resurveys of the structural crest and localized subsidence trajectories at semi-decadal to decadal intervals, ideally employing precision techniques such as RTK-GNSS or satellite-based InSAR. Integrating these empirical local measurements with iteratively refined global mean sea-level projections—as they become available in subsequent Intergovernmental Panel on Climate Change (IPCC) assessment cycles—will facilitate a dynamic recalibration of the freeboard vulnerability matrix. Ultimately, this iterative feedback loop establishes a quantitative threshold for action, ensuring that physical interventions are executed only when environmentally dictated. By doing so, this approach effectively navigates the deep uncertainty inherent in long-term climate modeling, optimizing the allocation of engineering resources and systematically preventing both premature infrastructure investments and the risks of maladaptation.

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This continuous appraisal ensures that structural vulnerabilities can be re-evaluated well before the critical 'Moderate-risk' threshold is breached. Strategically, this proactive paradigm mitigates the risk of financial misallocation associated with premature structural overdesign, while guaranteeing that critical tipping points for physical intervention are identified with sufficient operational lead time. Such a methodology is highly congruent with the sophisticated, flexible adaptive pathway frameworks pioneered in contemporary Dutch delta management planning (Stive et al., 2020).

4. Conclusion

This study applied a freeboard-based overtopping risk classification to the Sirenja Beach polder, Central Sulawesi, using water-level outputs from a companion Delft3D hydrodynamic model. Maximum water level increased from 1.17 m to 2.17 m between the present-day and 100-year sea level rise scenarios, reducing available freeboard from 3.50 m to 2.50 m, a 29% reduction. Despite this trend, both scenarios remain within the Low-risk category under the applied four-tier classification, and the resulting freeboard compares favorably against subsidence-affected polder systems elsewhere in Indonesia. The results support a monitoring-triggered rather than immediate structural adaptation strategy, with periodic resurvey of crest elevation and subsidence rate recommended as the key trigger mechanism for future intervention decisions. The freeboard classification framework applied here offers a low-data, transferable screening tool that could be extended to other post-disaster coastal protection structures across tsunami-affected regions of Indonesia.

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