The Influence of the Armor Stability Coefficient on the Hydraulic, Economic, and Environmental Performance of Rubble Mound Breakwaters

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ABSTRACT

The climate change and sea level rise are increasing the need for resilient and sustainable coastal protection. Breakwaters are essential for mitigating the erosion and flooding, and the stability coefficient (K_D) of armor units plays a critical role in determining the hydraulic performance, material quantities, and sustainability. However, limited research has explored how varying K_D affects the armor unit weight, embodied carbon, and construction costs. This study investigated the relationship between rubble and mound breakwaters designed under severe storm conditions. Hudson's formula was applied across a K_D range of 2–24 to represent natural rock and engineered concrete armor types. The required armor unit weights were calculated, and quantities were used to estimate the embodied carbon using a cradle-to-gate assessment and the total costs based on the Indonesian market prices. The results show that increasing K_D reduces the required armor weight from ~4.7 t to 0.4 t, embodied carbon per meter from 28 tCO_2e to 11 tCO_2e, and construction cost from 215 million to 85 million IDR per meter. However, the reductions plateaued beyond K_D values of 12–16, suggesting an optimal range for balancing the stability, sustainability, and cost. These findings highlight that selecting an armor with a higher stability coefficient can significantly improve the environmental and economic performance of breakwaters, supporting a more sustainable coastal infrastructure that is resilient to extreme wave conditions.

Keywords-rubble mound breakwater; stability coefficient; armor unit design; embodied carbon; coastal engineering sustainability

I. INTRODUCTION

Global climate change has heightened the urgency for scientists and engineers to develop environmentally sustainable and resilient coastal structures. Littoral zones are expected to experience increasingly severe challenges, including higher design wave heights, unexpected overtopping, and elevated risks of coastal flooding due to structural damage [1-4]. Breakwaters serve as a primary line of defense in coastal protection by dissipating the wave energy, reducing the intensity of nearshore currents, and encouraging the sediment deposition, which together promote the beach accretion and shoreline stability [5-7].

A wide range of breakwater types, including detached and attached rubble mound structures and caisson breakwaters, are commonly used in coastal engineering. These structures are typically constructed using materials, such as natural rocks, concrete blocks, or steel. Traditionally, the armor layer of rubble mound breakwaters relies on large natural stones to withstand the forces of wave attack. However, the availability of high-quality natural stones of an adequate size is becoming constrained in many coastal regions owing to the resource depletion and stricter environmental quarrying regulations. This growing scarcity has driven a transition toward the use of prefabricated concrete armor units, such as tetrapods, dolosses, and tribars, which are engineered to enhance the interlocking and improve the energy dissipation performance. These artificial armor units can be fabricated with consistent shapes and dimensions under controlled conditions, allowing designers to achieve optimized hydraulic stability and predictable structural behavior. Consequently, concrete armor units have emerged as practical and effective alternatives to natural rock in modern breakwater construction, offering reliable performance and adaptability across diverse site conditions and design requirements [8-11].

The armor erosion due to wave attack one of the primary failure modes in the design of rubble mound breakwaters, underscoring the importance of ensuring adequate hydraulic stability of the armor layer. Consequently, research has focused on understanding and improving the performance of various armor units under different wave conditions. Authors in [12] investigated the stability of concrete armor blocks subjected to solitary waves through hydraulic model experiments on breakwaters constructed with wave-dissipating units. Authors in [13, 14] conducted both physical model tests and numerical analyses to examine the stability of armor layers positioned behind composite breakwaters during tsunami wave overtopping. Authors in [15] evaluated the hydraulic stability of bloc armor units and assessed their influence on reducing the overtopping rates. Authors in [16] performed physical model tests on cube-armored mound breakwaters exposed to depth-limited breaking waves, revealing that their measured stability was lower than that of predictions based on traditional empirical formulas. To enhance the breakwater stability while minimizing the construction costs and material consumption, authors in [17] explored the performance of high-density concrete cubes used as armor units. Collectively, these studies highlight the experimental and numerical research dedicated to characterizing the hydraulic behavior of the armor layers and improving the breakwater design.

Despite the research on the hydraulic stability of various armor units, most studies have focused primarily on evaluating the physical performance under wave and tsunami conditions, with limited attention given to the broader sustainability and economic implications of the armor design choices. Existing investigations have rarely quantified how the variations in the stability coefficient of the armor units influence the required armor size, associated embodied carbon emissions, and overall construction costs. This lack of integrated assessment represents a critical research gap, particularly because coastal engineering demands solutions that balance the hydraulic performance with environmental and economic considerations. Therefore, the objective of this study is to evaluate the effects of different stability coefficients on the required armor size, embodied carbon footprint, and total construction cost of rubble mound breakwaters, thereby providing a comprehensive basis for selecting armor types that optimize both the structural stability and sustainability in modern coastal protection projects.

II. METHODOLOGY

The present study evaluated the required armor unit weight and quantity for various stability coefficients to assess their effects on the armor layer performance, embodied carbon, and construction cost in rubble mound breakwaters. The analysis focused on the primary armor layer, as illustrated in Figure 1, which presents a typical cross-section of the breakwater considered in this study. The structure consists of a core layer, a filter layer, and an outer armor layer exposed to a wave attack.

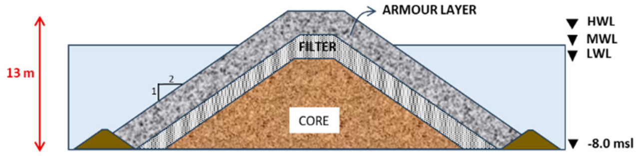

Fig. 1. Breakwater configuration used in the study.

Hydrodynamic design parameters were established to represent the severe storm conditions typical of exposed coastal environments. A significant wave height (H) of 3.0 m and peak wave period (T) of 10 s were adopted for the stability calculations, consistent with the extreme wave events expected during design-level storms. Water level variations were incorporated to capture the range of possible scenarios affecting the armor stability, with High Water Level (HWL) at +1.85 m, Mean Water Level (MWL) at +1.05 m, and Low Water Level (LWL) at +0.30 m relative to the chart datum. These water levels ensure that the analysis considers the most critical conditions, including the combination of the maximum wave attack and elevated water levels that increase the overtopping risk and impose higher forces on the armor layer.

The total crest height of the breakwater (H_{BW}) is determined to ensure that the structure prevents overtopping under the designed wave conditions. The height was calculated using:

$$H_{BW} = E_{SB} + HWL + R_u + 0.5 \qquad (1)$$

where E_{SB} is the elevation of the seabed level, R_u is the estimated wave run-up, and an additional freeboard (0.5 m) was included for safety considerations.

The wave run-up (Ru) was estimated using the Iribarren number (I_r), which characterizes the relationship between the slope steepness and wave conditions. First, the deepwater wavelength (L_0) was calculated as:

$$L_0 = 1.56T^2 \qquad (2)$$

where T is the peak wave period. The Iribarren number is then obtained using [18]:

$$I_r = \frac{\tan\theta}{\sqrt{H/L_0}} \qquad (3)$$

where θ is the slope angle of the armor layer and H is the significant wave height. The empirical relationship between I_r and the relative wave run-up (Ru/H) is used to estimate Ru, ensuring the consideration of critical wave attack scenarios.

The stability of the armor layer was ensured by calculating the required individual armor unit weight (W) using Hudson's formula [19]:

$$W = \frac{\gamma_r H^3}{K_D\left({}^{\gamma_r}/_{\gamma_a} - 1\right)^3 \cot\theta} \qquad (4)$$

where γ_r and γ_a are the unit weights of the armor material (concrete) and seawater, respectively, and K_D is the stability coefficient of the armor unit.

The total number of armor units required (N) was then determined to ensure the complete and stable coverage of the armor layer area (A), considering the placement porosity:

$$N = Ank_\Delta\left(1 - \frac{P}{100}\right)\left(\frac{\gamma_r}{W}\right)^{2/3} \qquad (5)$$

where n is the minimum number of the armor units across the crest (typically > 2), k_Δ is the layer coefficient (1.04), and P is the armor porosity percentage (taken as 50%).

In this study, it was assumed that all armor units were constructed using unreinforced concrete. The use of plain (non-reinforced) concrete reflects the standard practice for mass-produced armor units, such as tetrapods, dolosses, and cubes, which rely on their geometric interlocking and mass for stability rather than reinforcement. To evaluate the effects of different armor stability characteristics on the required armor size, embodied carbon, and construction cost, the stability coefficient (K_D) was systematically varied across a range of values representative of commonly used armor types. Specifically, K_D was varied from 2 to 24, covering typical values for natural rock armor (low K_D around 2–3), as well as engineered concrete armor units, such as tetrapods, dolosses, and high-performance interlocking units (higher K_D values up to 24). This range was chosen to capture the full spectrum of the armor stability coefficients encountered in practical breakwater design, hence enabling a comprehensive assessment of how increasing the armor stability influences the required armor unit weight, total armor quantity, and the associated sustainability and economic outcomes.

The embodied carbon of the concrete armor units (E_C) was evaluated using a cradle-to-gate life cycle assessment framework, which includes stages A1-A3, as defined by BS EN 15978 [20]:

$$E_C = \sum(C \times CF) \qquad (6)$$

where C is the total quantity of the concrete used (in kg) and CF is the embodied carbon factor, taken as 0.138 $kgCO_2/kg$. This carbon factor corresponds to concrete grade C32/40, which is commonly used in marine structures and is based on a detailed inventory of carbon and energy compiled using the circular ecology approach [21]. By following established standards for life cycle assessment, this methodology ensures a consistent, transparent, and reliable evaluation of the embodied carbon associated with the production of unreinforced concrete armor units.

For the cost calculations, the unit price of concrete was taken as 2,500,000 IDR/ m^3, reflecting the average market rates for marine-grade concrete commonly used in coastal construction projects in Indonesia [22].

III. RESULTS AND DISCUSSION

Figure 2 displays the relationship between the stability coefficient (K_D) and the calculated required weight of the individual armor units. The results demonstrate an inverse relationship: as K_D increases from 2 to 24, the required armor unit weight significantly decreases from approximately 4.7 tons to around 0.4 tons. This trend is consistent with the theoretical expectations of Hudson's stability formula, which predicts that higher stability coefficients allow smaller, lighter armor units to achieve the same hydraulic stability under identical wave conditions. The most pronounced reduction in unit weight occurs at lower stability coefficient values ($K_D \leq 6$), where incremental increases in K_D yield substantial decreases in the required armor size. For instance, increasing K_D from 2 to 4 results in a reduction in the armor weight by more than 50%. However, as K_D exceeds 12, the rate of reduction in the armor weight decreases significantly, approaching an asymptotic trend, where further increases in K_D yield minimal additional benefits in reducing the unit size.

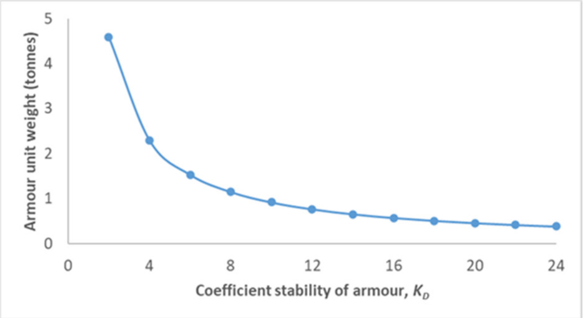

Fig. 2. Required armor unit weights for different stability coefficients of armor, K_D.

These findings highlight a critical practical consideration for the breakwater design: selecting armor units with higher stability coefficients (e.g., engineered concrete armor, such as tetrapods, dolosses, or accropodes) can dramatically reduce the required unit size and total volume of the armor material, thus decreasing both the embodied carbon and construction costs. However, the diminishing returns observed at higher K_D values suggest that beyond a certain point, further increases in the stability coefficient may not justify the potentially higher manufacturing complexity or costs of specialized armor units.

Following the analysis of the required armor unit weight, which demonstrated a strong inverse relationship between the stability coefficient and unit size, the embodied carbon associated with each design scenario was evaluated to understand the sustainability implications of varying armor stability. By linking the reductions in the armor unit weight to the corresponding decreases in the material quantities, the embodied carbon results provide critical insights into the environmental benefits achievable by selecting higher stability coefficients. Figure 3 illustrates the calculated embodied carbon per meter length of the breakwater as a function of the stability coefficient, enabling a comprehensive assessment of the carbon footprint across different armor configurations.

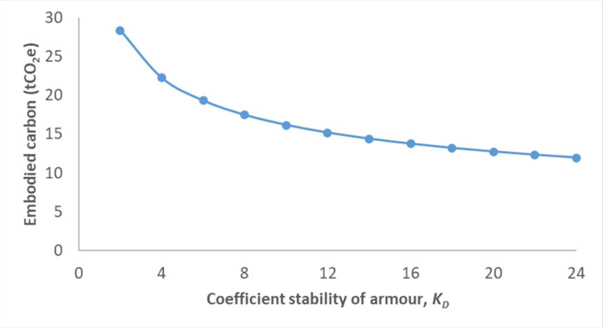

Fig. 3. Embodied carbon per meter length of breakwater for different slope configurations.

The results revealed a clear declining trend: as K_D increased from 2 to 24, the embodied carbon decreased significantly from approximately 28 to 11 tCO_2e per meter length of breakwater. This trend reflects the direct influence of the stability coefficient on the required armor unit weight and total concrete volume required for the armor layer. Higher K_D values allow for smaller and lighter armor units while maintaining the same hydraulic stability, leading to substantial reductions in the material consumption. Consequently, the embodied carbon, which is proportional to the quantity of concrete used, decreases as the stability coefficient increases.

Moreover, the results demonstrate that shifting from low-stability natural rock ($K_D \approx 2-3$) to high-stability engineered concrete armor ($K_D \geq 12$) can reduce the embodied carbon emissions by over 50% per meter of breakwater. However, similar to the trend observed in the armor weight analysis, the rate of embodied carbon reduction diminished beyond K_D values of approximately 12–16, indicating diminishing returns for further increases in the stability coefficient.

These findings have important sustainability implications. They confirmed that selecting armor types with higher stability coefficients can substantially lower the carbon footprint of breakwater construction by minimizing the concrete usage. This strategy supports the design of low-carbon coastal infrastructure, which is particularly important in regions where the climate change mitigation and carbon reduction targets are priorities. However, the observed diminishing returns suggest that there is an optimal range of stability coefficients beyond which the environmental benefits plateau, and the additional costs or the complexity associated with high-performance armor units may not be justified.

Building upon the embodied carbon analysis, which demonstrated significant environmental benefits associated with selecting higher stability coefficients, the economic implications of varying armor stability were also evaluated to provide a comprehensive assessment of the design choices. By correlating the reductions in the required armor quantities with the associated material and construction costs, the cost analysis offers insights into the financial advantages of optimizing the armor stability. Figure 4 presents the estimated total construction cost per meter length of breakwater as a function of the stability coefficient, allowing a direct comparison of the economic outcomes alongside technical and environmental performance.

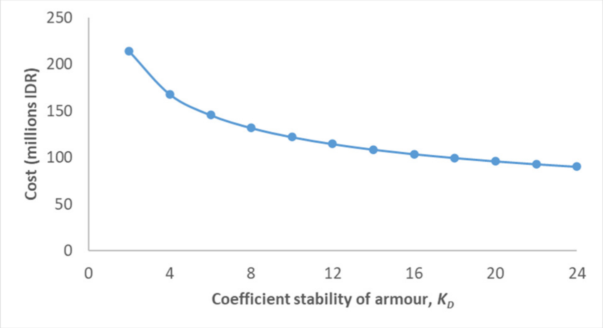

Fig. 4. Cost per meter length across different slope configurations.

The results demonstrate that as the stability coefficient increases from 2 to 24, the total cost of the armor layer decreases substantially, from approximately 215 million IDR to approximately 85 million IDR/m. This declining trend directly corresponds to the reductions in the required armor unit weight and quantity observed at higher stability coefficients. As K_D increases, the necessary size and number of armor units decrease, resulting in significant savings in the material costs, fabrication expenses, transportation, and installation activities. The most notable cost reductions occur at lower stability coefficient ranges ($K_D \leq 8$), where incremental increases in K_D yield large decreases in the total cost. Beyond a stability coefficient of approximately 12, the rate of cost reduction tapers off, indicating diminishing economic returns for further increases in the armor stability.

The combined analysis of the embodied carbon and construction costs highlights important practical implications for the design and implementation of rubble mound breakwaters. The results demonstrate that increasing the stability coefficient of the armor units not only reduces the required material quantities and unit sizes, but also provides environmental and economic benefits. Specifically, adopting armor types with higher stability coefficients can lower the embodied carbon emissions by more than 50% and reduce the construction costs by over 60% compared to the designs employing low-stability natural rock armor.

These findings are consistent with the trends observed in previous experimental and numerical studies, such as [12, 16], which focused on the armor stability under wave loading. However, these studies primarily assessed the structural performance without evaluating the environmental or economic metrics. In contrast, this study presents a novel contribution by integrating embodied carbon and cost assessments into the evaluation framework. By quantifying how the stability coefficient influences not only the armor weight, but also the sustainability and cost metrics, this work fills a critical gap in the literature. This multidimensional approach enables a more holistic understanding of the breakwater design performance and supports the development of sustainable and cost-efficient coastal infrastructure solutions.

From a practical perspective, these findings support the selection of engineered concrete armor units with optimized stability characteristics—such as tetrapods or other interlocking shapes—as a means of achieving more sustainable and cost-effective coastal protection. This strategy is particularly valuable in regions where the availability of large natural rocks is limited, quarrying is environmentally restricted, or the transportation costs are high. By minimizing the concrete volumes using higher stability coefficients, projects can reduce the material consumption, lower the greenhouse gas emissions associated with construction, and achieve significant savings in production, transport, and installation costs.

However, the observed diminishing returns beyond stability coefficients of approximately 12–16 suggest that specifying excessively high-performance armor units may not yield proportional additional benefits and could instead introduce unnecessary complexity or higher unit prices. Therefore, designers should aim to identify an optimal range of stability coefficients that balances the hydraulic stability, embodied carbon reduction, and cost efficiency, ensuring that resilient and environmentally responsible breakwater designs align with the contemporary sustainability targets.

IV. CONCLUSIONS

This study evaluated the influence of the stability coefficient (K_D) on the required armor unit weight, embodied carbon emissions, and construction costs for rubble mound breakwaters under severe coastal storm conditions. The results demonstrated a strong inverse relationship between the K_D and armor unit weight, with the required unit mass decreasing from approximately 4.7 tons at $K_D = 2$ to around 0.4 tons at $K_D = 24$. Correspondingly, the embodied carbon per meter length of breakwater declined by over 50% as the stability coefficient increased, reflecting the substantial reductions in the concrete volume, achievable through higher-performance armor units.

The economic analysis exhibited similar trends, with the total construction costs per meter dropping by more than 60% across the examined K_D range. These results emphasize that selecting armor types with higher stability coefficients, such as engineered interlocking concrete units, can significantly improve both the environmental performance and cost efficiency of the breakwater designs. However, the diminishing returns observed beyond K_D values of approximately 12–16 indicate that extremely high-performance armor units may offer limited additional benefits, underscoring the importance of optimizing the stability coefficient selection to balance the hydraulic stability, sustainability, and economic considerations.

Overall, this study stresses the significant role of the stability coefficient in achieving resilient, low-carbon, and cost-effective coastal protection structures. Unlike previous research that focused primarily on the hydraulic performance, this study integrates structural, environmental, and economic perspectives into a unified evaluation framework. The findings provide a novel contribution by quantifying how the variations in the stability coefficient influence not only the armor weight, but also the embodied carbon and construction costs. This integrated approach offers valuable insights for the sustainable design of rubble mound breakwaters and supports informed decision-making aligned with climate-resilient coastal engineering practices.

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DATA AVAILABILITY

Data analysis https://zenodo.org/records/15795932.

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