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Hydraulic design recommendations for eco-engineered single-layer armour units

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ABSTRACT

This paper presents the first consolidated hydraulic design recommendations for the Coastalock™ armour unit, an eco-engineered single-layer armour system. Based on 306 individual sea-state test runs from four independent physical modelling campaigns conducted at the National Research Council Canada (NRC) and at Delft University of Technology (TU Delft), this study establishes a consolidated empirical basis for design. Hydraulic performance was expressed in terms of the stability number (N_s) and the Hudson coefficient (K_D) for both permeable and impermeable cores with 2V:3H and 1V:2H slopes. The best-performing configuration (for a 2V:3H slope) consisted of protruded Coastalock units at 22.5% spacing on a permeable core; the resulting preliminary design values were $N_s \approx 2.8$ and $K_D \approx 15$, which fall within the range reported for established single-layer systems such as Core-Loc™, Xbloc™, Accropode II™, and Cubipod®. Armour unit spacing (defined as the intentional lateral gap between adjacent units expressed relative to the nominal armour diameter) and underlayer sizing were identified as the main effective parameters for hydraulic stability. The best performance for the tested configurations was observed for underlayer-to-armour layer nominal diameter ratios between 0.25 and 0.34, interpreted within the tested spacing, core permeability, and placement conditions. Overtopping analysis, calibrated against EurOtop formulas, produced γ_f values primarily between 0.65 and 0.70, reflecting the overtopping characteristics of Coastalock. Ecological monitoring is acknowledged as design context, as the unit cavities can function as water-retaining tidal pools and shaded refuges; however, the recommendations presented here are focused on hydraulic stability, overtopping, underlayer response, and toe/rear side response observations. These findings indicate that Coastalock has potential as a dual-purpose single-layer armour unit. The recommendations based on the tested structural configurations and hydraulic conditions provide a research-based framework for preliminary hydraulic design of single-layer eco-engineered Coastalock armour units.

1. Introduction

The design of coastal protection structures has traditionally focused on providing reliable resistance against wave attack and storm surge, with rubble mound breakwaters and revetments forming the basis of modern shoreline defence systems. These structures are effective in dissipating incident wave energy and maintaining stability under extreme loading conditions. However, the escalating pressures of climate change, evolving environmental standards, and coastal urbanization have amplified the demand for resilient and adaptable coastal defence systems, requiring innovative approaches that balance hydraulic stability, constructability, and long-term sustainability (Hinkel

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et al., 2014; Morris et al., 2020).

Concrete armour units are fundamental to rubble mound breakwater design because they provide high hydraulic stability while limiting material use. Modern proprietary single-layer systems such as Core-Loc™, Xbloc®, XblocPlus®, Accropode II™, and Cubipod® are supported by design manuals that define placement rules, stability coefficients, hydraulic performance parameters, and construction tolerances (USACE, 2002; Medina and Gómez-Martín, 2016; CLI, 2023; DMC, 2023).

Eco-engineering strategies have increasingly introduced surface texturing, cavities, tidal pools, and bio-enhancing concrete mixes into coastal protection elements to improve habitat heterogeneity while retaining hydraulic function (Browne and Chapman, 2011; Sella and Perkol-Finkel, 2015; Sella et al., 2022). For armour systems, these ecological features should be treated as geometric and material modifications whose hydraulic implications require direct testing.

The Coastalock armour unit was developed in 2021 to combine modern single-layer hydraulic performance with ecological design features. Its interlocking geometry supports regular placement, while integrated cavities and textured surfaces provide shaded, moisture-retaining microhabitats across tidal elevations (Sella and Perkol-Finkel, 2015; Gutiérrez Martínez et al., 2023).

Since its development, Coastalock has been tested in several physical modelling campaigns. Molenkamp (2022) examined impermeable-core revetments; Ławniczak (2024) investigated permeable rubble mound slopes with variations in spacing, underlayer support, toe support, protrusions, and unit orientation; Sayar et al. (2025) tested low-crested and emergent RMBWs, with complementary experimental–numerical assessment of wave transmission and overtopping provided by Sayar et al. (2026); and Baker et al. (2023) evaluated milder-slope impermeable-core revetments. Together, these studies provide the basis for the consolidated analysis presented here.

Unlike established proprietary systems such as Core-Loc, Xbloc, Accropode II, and Cubipod (which are supported by detailed design manuals defining stability numbers, Hudson coefficients, and overtopping roughness factors), Coastalock currently lacks consolidated design recommendations for engineering applications. The absence of such guidance creates uncertainty for designers, as results from existing experimental studies remain scattered across different configurations and test conditions. Developing a unified preliminary hydraulic design framework is therefore essential to support the use of Coastalock in practical projects.

This study aims to develop the first consolidated set of preliminary hydraulic design recommendations for the ecologically engineered (eco-engineered) Coastalock single-layer armour unit, integrating findings from multi-institutional two-dimensional physical modelling campaigns. By systematically analyzing hydraulic stability numbers (N_s), Hudson coefficients (K_D), overtopping roughness factors (γ_f), toe and rear side stability response, and underlayer-to-armour size ratios, the paper derives data-supported design recommendations that extend existing rubble mound design practice to Coastalock configurations. The paper focuses on tested trunk-section configurations and hydraulic recommendations directly supported by the available physical model data. Ecological functionality is considered as design context for the unit, while detailed biological performance is not analyzed in the present paper focused on hydraulic performance.

2. Background and design parameters

2.1. Coastalock development and prior studies

The Coastalock armour unit (Fig. 1A) was specifically developed to combine hydraulic performance with ecological functionality and regular placement by integrating geometric and material innovations into a single-layer armour element. Its geometry enables regular placement at controlled lateral spacings, as illustrated by the field placement shown in Fig. 1B. Unit spacing refers to the intentional lateral gap between adjacent Coastalock units, expressed in this study relative to the nominal armour diameter as defined in Section 3.1. This spacing governs the porosity of the armour layer, influencing internal flow penetration, uplift pressures, and interlocking performance. Although placement density can vary for many single-layer armour units within recommended limits, spacing was treated as a primary and systematically varied design parameter in the Coastalock experimental program. While the cavity volume of individual Coastalock units is fixed and independent of spacing, increased spacing may also increase the exposed inter-unit void area within the armour layer, which is relevant to both hydraulic porosity and habitat availability. In addition, larger spacing reduces the total number of units required, thereby decreasing concrete consumption for a given design condition.

Distinct from conventional systems, Coastalock incorporates a cavity in the centre of the unit that can be placed with different orientations (cavity upward, sideways, and downward), creating multiple habitat features: water-retaining niches, caves, overhangs, and shaded refuges across tidal elevations, which aim to support colonization by diverse marine organisms at different life stages (Fig. 1C). In addition, the unit is cast using a bio-enhancing concrete formulation and incorporates micro-textured surfaces that improve larval settlement and long-term adhesion (Sella and Perkol-Finkel, 2015; Gutiérrez Martínez et al., 2023). These combined features position Coastalock as an eco-engineered alternative intended to address both hydraulic and ecological performance objectives.

Field monitoring from the Living Ports installation at the Port of Vigo provides prototype-scale context for the Coastalock geometry. The project included 100 Coastalock units with an individual volume of $1.42\,m^3$ placed in the regular sloped arrangement shown in Fig. 2D;

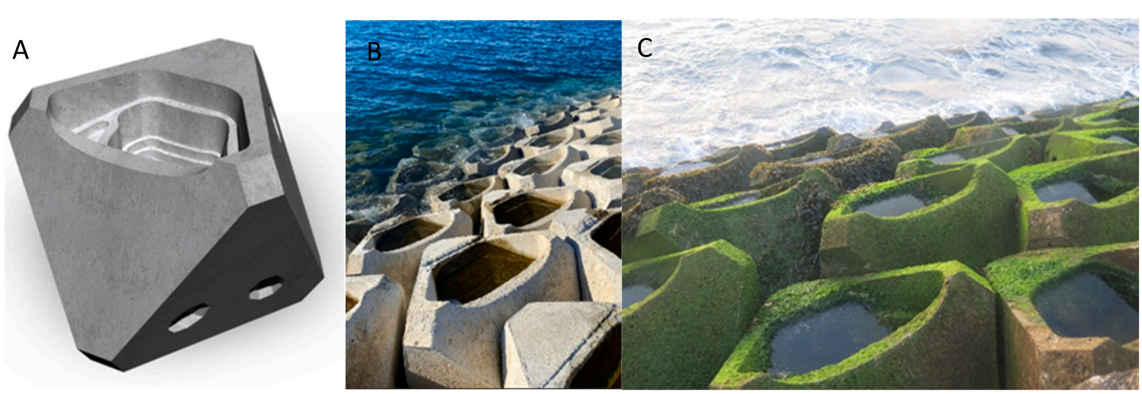

Fig. 1. Coastalock unit geometry and field-scale appearance: (A) unit geometry highlighting ecological cavities; (B) installed Coastalock units at the Port of Vigo, Spain; and (C) installed units after one year of exposure, showing biological growth on the unit surfaces.

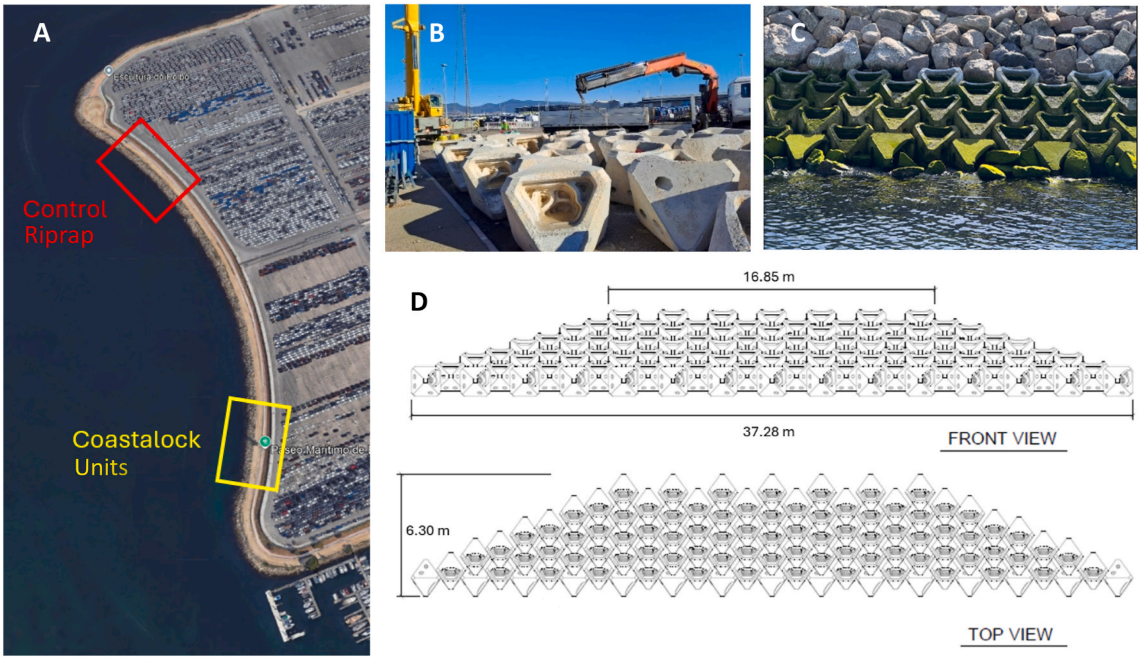

Fig. 2. Field application of Coastalock units at the Port of Vigo, Spain: (A) aerial view of the sloped protection showing the Coastalock installation area and adjacent control riprap; (B) Coastalock units after demoulding; (C) Coastalock units after installation on the sloped protection; and (D) front and plan views of the installed Coastalock arrangement. Dimensions are in metres. Units and control riprap are indicated in the figure.

biological observations are retained only as context for the eco-engineered unit concept (ECOncrete, 2024).

While field applications enable gathering the prototype scale observations and biological data, experimental campaigns have examined Coastalock performance across a wide range of structural and hydraulic conditions, including impermeable-core revetments (Molenkamp, 2022) and permeable-core revetments (Ławniczak, 2024) in deeper water with unit spacing, protrusion, and orientation variations, emergent RMBWs with hydraulic stability and performance outcomes (Sayar et al., 2024), and milder-slope revetments with an impermeable core under diverse wave conditions (Baker et al., 2023).

2.2. Eco-engineering in coastal structures

Eco-engineering strategies for coastal infrastructure have been increasingly adopted to reduce biodiversity loss associated with conventional hard coastal protection systems (Moschella et al., 2005; Firth et al., 2016; Strain et al., 2018). These strategies include surface texturing, artificial rock pools, ecological cavities, bio-enhancing concrete formulations, and other geometry-based modifications that increase habitat heterogeneity compared with smooth concrete or conventional armour rock (Browne and Chapman, 2011; Sella and Perkol-Finkel, 2015; Hall et al., 2018; Morris et al., 2020).

Surface protrusions on revetments are a well-established means of reducing overtopping on dike revetments, as reflected in the roughness factors presented in the (EurOtop, 2018) . In a flume experiment focused on vertical walls, surface protrusions reduced mean overtopping rates by increasing roughness (Salauddin et al., 2021). However, most studies provide limited evidence regarding stability impacts on rubble mound or armour units placed on steep slopes, and many authors mention that any hydraulic benefit depends heavily on geometry, wave regime, and placement configuration (Salauddin et al., 2021; Perricone et al., 2023). Therefore, while surface enhancements may be hydraulically promising, their influence must be evaluated case by case rather than assumed to be universally beneficial. For Coastalock, this reinforces the need to interpret ecological features, protrusions, and placement arrangements as tested geometric variables whose hydraulic implications are evaluated from physical model data.

2.3. Design parameters in established armour unit guidelines

Design manuals for proprietary armour units provide engineers with explicit stability numbers (N_s), Hudson coefficients (K_D) (defined in Section 3.3), and overtopping roughness factors (γ_f) (defined in Section 3.5) derived from systematic physical model studies.

The hydraulic stability of armour layers is generally described in terms of either K_D or N_s (USACE, 1984; USACE, 2002). Historically, Hudson's formula (Hudson, 1959), which assumes regular wave conditions, provided a simple way to determine the required armour unit weight without incorporating the effects of parameters such as wave steepness, storm duration, or structure permeability. As a result, its direct applicability to interlocking single-layer armour systems is limited, and K_D values for such systems are generally used as comparative design parameters rather than as the primary basis for stability assessment. Therefore, reported Hudson coefficients (K_D) for such systems are often presented for comparison purposes only. Recommended Hudson coefficients vary widely by unit type, placement, and slope steepness application. For quarried rock in non-breaking waves, typical values are $K_D \approx 3$–4, whereas double-layer concrete shapes such as cubes or Tetrapods achieve K_D values around 6–8 (USACE, 1984; Ciria and Cetmef, 2007).

Van der Meer (1988) extended these approaches to irregular wave conditions and variable damage levels, showing that stability of rock slopes decreases with wave steepness and storm duration, while a limited degree of damage may be acceptable for double-layer armours. For single-layer interlocking units (such as Accropode, Core-Loc, and Xbloc), the recommended design practice allows no damage (i.e., no large unit displacements or extractions) at the design wave height because these systems often exhibit brittle damage behaviour, where the initial extraction of one unit can rapidly lead to progressive damage. In physical model testing of such interlocking systems, stability criteria typically distinguish between acceptable rocking motion and

Table 1
Typical hydraulic design constants for rock slopes and established armour units.

Type of armour unit	Design stability number (N_s)	Hudson coefficient (K_D)	Overtopping roughness factor (γ_f)
Accropode II	2.5 [a,c]	12	0.46
Core-Loc	2.8 [a,c]	16	0.44
Cube	2.2 [b,c]	7	0.47
Cubipod	2.5 [b,d]	12	0.47
Dolos (double layer)	2.5 [b,c]	12	0.43
Tetrapod (double layer)	2.2 [b,d]	7	0.38
Xbloc	2.8 [a,c]	13	0.44
XblocPlus	2.5 [a,c]	12	0.45

[a] Design N_s, corresponding K_D and γ_f for a 3V:4H slope.
[b] Design N_s, corresponding K_D and γ_f for a 2V:3H slope.
[c] No-damage condition.
[d] Initial-damage condition.

unacceptable unit displacement or extraction. Manufacturers commonly impose limits on allowable rocking during testing to prevent unit breakage, as excessive rocking may precede structural damage of the unit itself or progressive layer destabilization. Thus, the “no damage” condition refers to the absence of significant displacement or extraction of armour units, while limited rocking may still occur. Consequently, the design N_s for single-layer systems are typically in the range of $N_s = 2.4–2.8$, corresponding to K_D of 12–16 (for the 2:3 or 3:4 slopes applied), depending on slope steepness and placement density (Melby and Turk, 1997; Bakker et al., 2003; Reedijk and Muttray, 2009).

Another important parameter for design is the roughness factor γ_f used in overtopping assessments (EurOtop, 2018). Rough, porous armour layers reduce wave run-up and overtopping by increasing turbulence and energy dissipation. Typical γ_f values are about 0.40 for rock armour in a double layer and 0.44–0.47 for most single-layer armour units (Bruce et al., 2009). Since higher γ_f values correspond to less overtopping reduction, the roughness factor provides a direct basis for comparing overtopping performance among armour types.

Table 1 summarizes representative design parameters for conventional and proprietary armour units. The N_s and K_D values correspond to preliminary design conditions for breakwater trunk sections under breaking waves (USACE, 1984; van der Meer, 1988; USACE, 2002; Ciria and Cetmef, 2007; Bruce et al., 2009; Reedijk and Muttray, 2009; Medina and Gómez-Martín, 2016; CLI, 2023; DMC, 2023), and the γ_f values are roughness factors from the (EurOtop, 2018).

2.4. Research gaps and study objectives

The available literature on Coastalock has provided important insights into hydraulic stability, unit spacing effects, underlayer requirements, and overtopping performance across different structural configurations. However, these findings are dispersed among separate studies and have not yet been unified into a consolidated basis for preliminary hydraulic design. Conventional single-layer units such as Accropode II, Xbloc and XblocPlus, Cubipod, and Core-Loc are supported by well-established guidelines that provide explicit stability numbers, design equations for armour sizing, and clear recommendations on underlayer size and overtopping protection (USACE, 2002; Medina and Gómez-Martín, 2016; CLI, 2023; DMC, 2023).

Currently, several Coastalock applications (European Commission, 2023; ECOncrete, 2023, 2024) have been implemented at the Port of San Diego (USA), the Port of Vigo (Spain), the Port of Bilbao (Spain), and the Port of Prince Rupert (Canada), with a standard unit size (1.42 m^3), while a bigger unit size (2 m^3) was used for more challenging climatic conditions in Monaco. For Coastalock, no comparable set of design-oriented recommendations exists, leaving practitioners uncertain about how to transform experimental results into engineering guidelines. This limits the ability of designers to select unit spacing, underlayer support, overtopping roughness factors, and toe configurations using a consistent hydraulic basis.

Accordingly, the objective of this study is to synthesize the available two-dimensional physical model results to derive preliminary hydraulic design recommendations for armour-layer stability, underlayer configuration, overtopping performance, and toe and rear-side response. The study does not attempt to provide a universal design manual for all Coastalock applications, but rather an interpretation of the available physical model evidence. The analysis focuses on tested trunk-section configurations and distinguishes between tested hydraulic behaviour, conservative interpretation of the available data, and applications requiring additional physical model verification, while ecological functionality is retained as part of the Coastalock design context.

3. Materials and methods

3.1. Summary of coastalock experiment datasets

This study relies on the synthesis of experimental results collected across multiple institutions to establish a consolidated empirical basis for preliminary hydraulic design recommendations for Coastalock. Four experimental campaigns conducted at Delft University of Technology (TU Delft) (Molenkamp, 2022; Ławniczak, 2024) and the National Research Council Canada (NRC) (Baker et al., 2023; Sayar et al., 2025), provide the most comprehensive dataset currently available and serve as the empirical basis for the hydraulic performance and analyses presented in this paper. The structural layouts tested in these campaigns are illustrated in Fig. 3, while the corresponding hydraulic and geometric parameters are summarized in Table 2.

The experimental campaigns tested a variety of structural configurations representative of conventional rubble mound coastal structures. These included revetment slopes of 2V:3H (as shown in Fig. 3A, B and 3C) and 1V:2H (in Fig. 3E), as well as an emergent RMBW (in Fig. 3D) with a 2V:3H front and rear slope. The test sections differed in the presence or absence of a foreshore, water depth, slope steepness, toe configuration, underlayer grading and thickness, core permeability, crest elevation and material, and armour unit spacing and orientation, which provide a diverse basis for assessing the hydraulic stability and performance of Coastalock units under multiple design conditions. Although additional experiments on submerged breakwater configurations were performed as part of Sayar, 2026, these are intentionally excluded from the present synthesis, which focuses on emergent structures.

Different Coastalock unit orientations were adopted across the experimental programs to investigate how cavity position and regular placement influence hydraulic stability. The San Diego arrangement denotes a mixed placement with sideward cavities below the low-water level and forward-facing cavities in the upper rows. Cavity-sideways and cavity-forwards arrangements isolate each of these orientations, respectively, while cavity-downwards refers to placement with the cavity opening directed toward the underlayer. PO-SWL and PO-Midpoint refer to protruded-unit arrangements positioned relative to the still-water level and the vertical midpoint of the armour layer, respectively. The cavity-forward orientation relative to the still-water level is illustrated in Fig. 4 as an example of the vertical placement convention used in the dataset.

Armour unit spacing, S, was defined as the intentional lateral gap between adjacent units, expressed relative to the nominal armour diameter ($D_{n,CL}$). It was calculated from the measured horizontal centre-to-centre distance between adjacent units, d_{cc}, as shown in Equation (1):

$$S(\%) = \frac{d_{cc} - D_{n,CL}}{D_{n,CL}} \times 100 \quad (1)$$

A specific feature in Ławniczak (2024) was the inclusion of protrusions (refer to Fig. 5) in the armour units tested to enforce the unit spacing as for 10% and 22.5% spacing. These protrusions are small extensions integrated into the Coastalock geometry to maintain the target gap between adjacent units, support interlocking, and reduce local migration of underlayer material under wave loading. Because protrusions modify both spacing and unit geometry, the 10% and 22.5% protruded configurations were treated separately from standard Coastalock configurations in the stability interpretation.

As summarized in Table 2, the dataset covers stability numbers approximately within the range $N_s \approx 0.49$–4.66 and relative wave heights $(H_s/h) \approx 0.03$–0.90, indicating coverage from low loading to design-level conditions with a range of wave steepness (S_{op}) values (1.7%–6.6%), variable crest geometries, and different underlayer and toe arrangements. The four campaigns were based on the same Coastalock unit concept and broadly comparable rubble mound geometries, although they differed in scale, flume facility, core type, slope, toe configuration, and hydraulic loading. The merged dataset consists of individual sea-state test runs grouped into test series corresponding to fixed structural configurations subjected to successive sea states. Although the dataset covers a broad range of wave heights, wave steepness values, underlayer sizes, and unit spacings, the variables are not uniformly distributed across all configurations. Therefore, the analysis supports configuration-specific interpretation rather than a fully general multivariate stability formula. Stability numbers were calculated using the test-specific Coastalock unit density and water density reported in Supplementary Table S1–0 and S1-D. Table 2 presents study-level prototype-scale parameters for comparison; however, the stability number (N_s) was used as the scale-consistent dimensionless parameter for cross-campaign comparisons.

3.2. Database structure and test-run classification

In the consolidated database, a test run is defined as one hydraulic sea state applied to a fixed structural configuration. A test series is defined as a sequence of sea states applied to the same structural configuration, typically with increasing wave height, until armour damage, a predefined limiting condition, or the maximum wave-generation capacity of the facility was reached. The 306 entries used in this study therefore represent individual sea-state test runs grouped within a smaller number of test series, rather than 306 statistically independent stability tests.

The database was organized by test series and by individual sea state. For each entry, the available structural, hydraulic, armour-layer, underlayer, toe, and response variables were compiled to support comparison among the four experimental campaigns. The variables

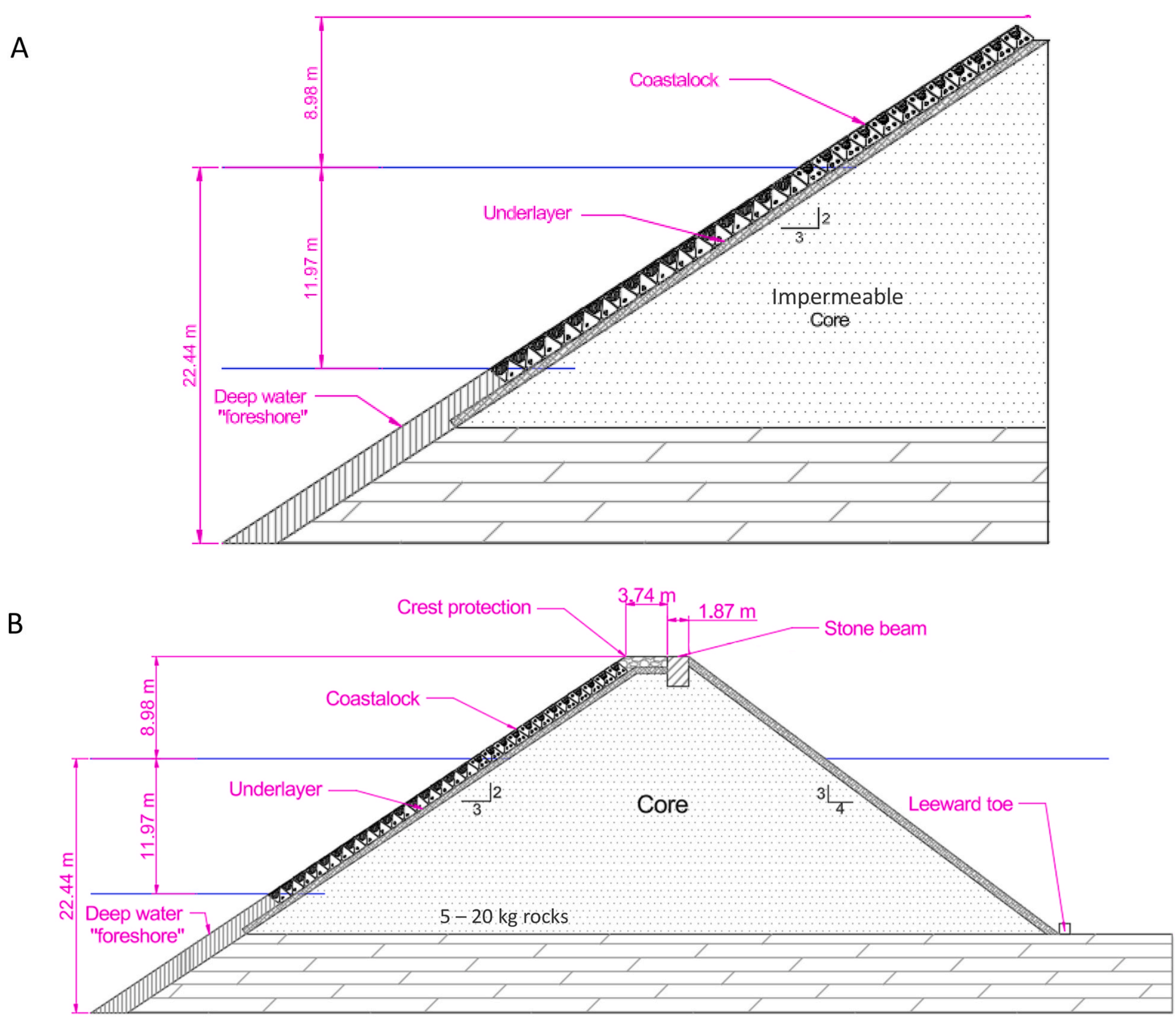

Fig. 3. Structural configurations (prototype scale) tested in Coastalock studies: (A) Molenkamp (2022), (B) structure without toe in Ławniczak (2024), (C) structure with toe in Ławniczak (2024), (D) Sayar et al. (2025) and (E) Baker et al. (2023).

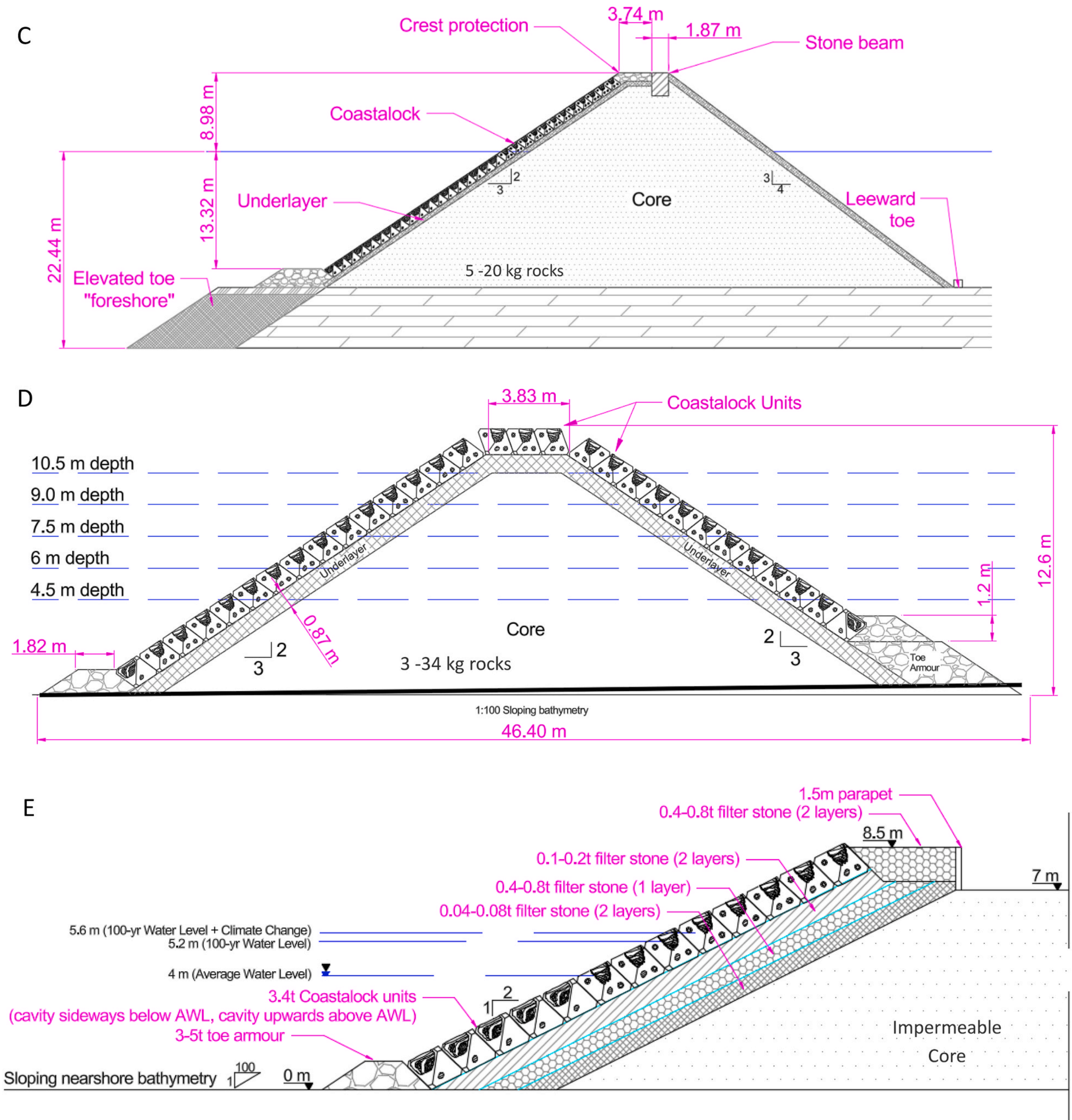

Fig. 3. (*continued*).

retained for the analysis are summarized in Table 3. Supplementary Table S1 provides the consolidated database, including the Molenkamp (2022), Baker et al. (2023), Ławniczak (2024), and Sayar et al. (2025) test runs. In this analysis, H_s is used as the general notation for significant wave height, while H_{m0} is retained in tables and figures where spectral significant wave height was reported directly by the original datasets.

3.3. Hydraulic stability analysis

The hydraulic stability of single-layer armour units was evaluated using the stability number (N_s), a non-dimensional index widely applied in rubble mound armour design and closely related to Hudson-type armour stability formulations. N_s is defined in Equation (2) as

$$N_s = \frac{H_s}{\Delta\, D_{n,CL}} \tag{2}$$

where H_s is the incident significant wave height, $D_{n,CL}$ is the nominal diameter of the armour unit, and Δ is the relative submerged density $\left(\Delta = \frac{\rho_{CL}}{\rho_w} - 1\right)$ with ρ_{CL} denoting the Coastalock unit density used for the corresponding test and ρ_W the water density. The N_s expresses the ratio between the applied wave loading and the resisting weight of the unit. This formula provides a direct comparison of armour performance across scales and configurations and serves as the reference parameter for subsequent design recommendations.

To establish design-relevant stability limits, N_s was calculated for each test run regardless of the instability occurrence using the measured

Table 2
Summary of key structural and hydraulic parameters for Coastalock physical model studies in the literature presented at prototype scale (PT refers to Coastalock units with protrusions).

Parameter/Study	Molenkamp (2022)	Ławniczak (2024)	Sayar et al. (2025)	Baker et al. (2023)
Scale	1/37.5	1/37.5	1/15	1/15
Breakwater type	Revetment	Revetment	Emergent RMBW	Revetment
Front slope	2V:3H	2V:3H	2V:3H	1V:2H
Significant wave height (H_s)	0.71 – 6.39 m	2.44 – 6.14 m	1.31 – 6.58 m	1.79 – 4.18 m
Corresponding stability number (N_s)	0.49 – 4.42	1.68 – 4.19	0.93 – 4.66	0.98 – 2.30
Wave steepness (s_{op})	2% – 6%	1.7% – 4.1%	3.1% – 6.5%	3.5% – 6%
Coastalock volume (m^3)	1.42 m^3	1.42 m^3	1.42 m^3	1.42 m^3
Model Coastalock volume (cm^3)	26.9 cm^3	26.9 cm^3	420.7 cm^3	420.7 cm^3
Nominal Coastalock density	2400 kg/m^3	2400 kg/m^3	2400 kg/m^3	2400 kg/m^3
Coastalock unit mass	3410 kg	3410 kg	3410 kg	3410 kg
Coastalock nominal diameter, $D_{n,CL}$ (m)	1.124 m	1.124 m	1.124 m	1.124 m
Model Coastalock nominal diameter, (m)	0.030 m	0.030 m	0.075 m	0.075 m
Armour layer thickness	1.25 m	1.25 m	1.25 m	1.25 m
Armour unit spacing	0%, 5%, 7.5%, 10%, 15%, 20%, 25%	0%, 10% (PT), 20%, 22.5% (PT)	10%	10%
Underlayer material diameter (D_{n50}, UL)	0/0.31 m	0.27 m	0.37 m	0.46 m
$d_{n50,UL}/D_{n,CL}$	0/0.278	0.249	0.333	0.414
Underlayer thickness	0.50 m (2 layers), 0.85 m (~3 layers)	0.60 m (2 layers)	0.87 m (~2 layers)	0.77 m (~2 layers)
Structure height	31.5 m	31.5 m	12.6 m	8.5 m
Crest width	0 m	5.61 m	4.5 m	4.0 m
Water depth at toe	22.4 m	22.4 m	4.5 m, 6.0 m, 7.5 m, 9.0 m, 10.5 m	4.0 m, 5.2 m, 5.5 m
Core type	Impermeable	Permeable	Permeable	Impermeable
Unit orientation	San Diego, Cavity Sideways, Forwards	San Diego, PO-SWL and Midpoint, Forwards	Cavity Forwards	Cavity Forwards
Coastalock unit design	Standard	Standard and CL with protrusions	Standard	Standard
Toe height	No toe	No toe/2.21 m	0.75 m	1.15 m
Toe width	No toe	No toe/3.30 m	2.25 m (3xD_{n50} wide)	2.30 m (2xD_{n50} wide)

significant wave height, armour unit size, and relative density. These values were then matched with the observed response category to determine the range of N_s associated with the onset of failure, defined here as visible armour unit displacement or extraction exceeding the stability criteria adopted in each experimental campaign. Rocking and breathing mechanisms (defined by Ławniczak, 2024) were retained as intermediate response modes, while displacement or extraction of armour units was treated as armour-layer instability. Toe-related failures were identified separately because they do not represent direct hydraulic instability of the Coastalock armour layer alone.

Since stability was recorded as a binary outcome, the exact critical condition cannot be observed directly but is constrained between consecutive test conditions. This is consistent with the discrete definition of damage levels in physical modelling, where continuous damage evolution is represented by threshold-based criteria (e.g., Vidal et al., 1991). Following common laboratory practice for threshold-type phenomena, the critical condition was therefore identified by interpolating stability numbers between the highest stable and lowest unstable runs. Where failure was not reached during a test series, the highest stable N_s was interpreted as a lower-bound estimate of the critical stability number rather than as the actual failure threshold. This provides a single representative threshold consistent with stability limits derived from discrete experimental observations and damage-based design approaches (van der Meer, 1988; CIRIA and CETMEF, 2007), and comparable to the deterministic stability numbers of Hudson (1959) and van der Meer (1988).

In line with the objective of proposing a baseline design configuration for practical applications, the stability analysis focused on tests of both permeable and impermeable core sections. For each configuration, the critical N_s was used to calculate the corresponding K_D through the classical Hudson (1959) relationship, as shown in Equations (3) and (4):

$$W = \frac{\gamma_r {H_s}^3}{K_D \Delta^3 \cot\theta} \tag{3}$$

$$K_D = \frac{N_s^3}{\cot\theta} \tag{4}$$

where W is the armour unit weight, γ_r is the unit weight of the armour material, α is the slope angle, and K_D is the Hudson stability coefficient. The K_D values are reported only as design-comparison parameters because the stability assessment itself is based on irregular-wave physical model results expressed through N_s.

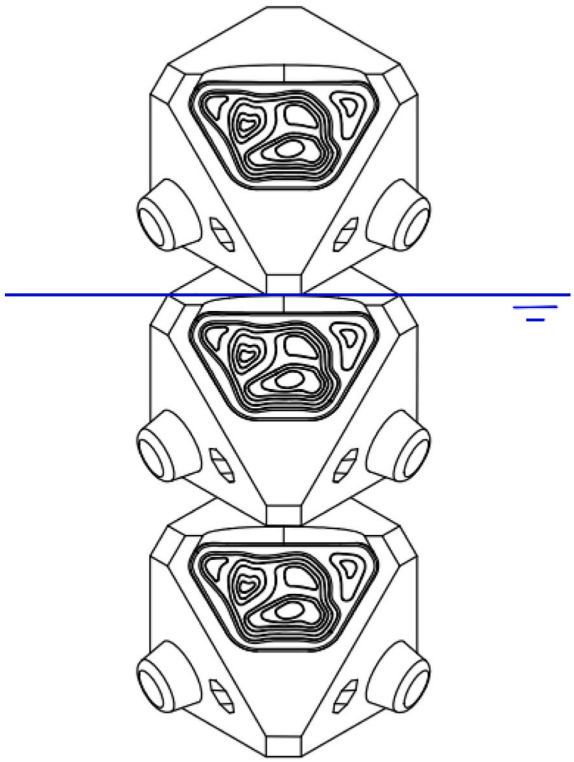

Fig. 4. Vertical arrangement of Coastalock armour units on a slope in a cavity-forward orientation relative to the still water level (SWL).

In line with conventional practice in rubble mound armour design, a safety factor is typically applied to laboratory-derived N_s to account for prototype uncertainties related to wave climate, construction tolerances, and scale effects (USACE, 2002; CIRIA and CETMEF, 2007). Considering these established recommendations and recognizing the distinctive geometry, placement precision, and interlocking mechanism of the Coastalock unit, a global safety factor of 1.5 was applied to the experimentally determined critical N_s values to account for experimental scatter, scale effects, and the limited number of observations. When only a lower-bound critical value was available because no failure occurred, the same safety factor was applied to the highest tested N_s, leading to a conservative design value within the tested range.

As an additional consistency check, lower-tail statistical estimates were considered for subsets containing comparable configurations and sufficient independent observations. These estimates were used only to assess whether the selected safety-factor-based design values were broadly consistent with the lower range of observed critical stability numbers.

Table 3
Variables retained in the consolidated Coastalock test-run database.

Category	Variables retained in the database
Test identification	Study, test series, test run ID, model scale
Section characteristics	Structure type, core permeability, crest height, front slope, water level at toe
Armour layer	Armour unit type, spacing, protrusions, and unit orientation
Underlayer	$D_{n50,UL}$, underlayer thickness and $D_{n50,UL}/D_{n,CL}$
Sea-state characteristics	Incident H_{m0} at the structure toe, reflected H_{m0}, reflection coefficient K_r, peak period T_p, mean period T_m, number of waves, wave steepness s_{op}, incident wavelength L, test duration
Measured response	Armour instability observed, and mean overtopping discharge (q)
Derived parameters	Stability number N_s, relative freeboard R_c/H_{m0}, and non-dimensional overtopping discharge (q*)

The statistical interpretation should be regarded as exploratory. The individual sea-state test runs are grouped within a smaller number of sequential test series and therefore cannot be treated as fully independent stability observations. In addition, the consolidated dataset combines different core types, slopes, unit spacings, orientations, toe configurations, underlayer gradings, and laboratory scales. Therefore, the statistical checks presented here are used only to assess the consistency and conservatism of selected design values. They should not be interpreted as a formal probabilistic stability calibration or as a predictive stability model for Coastalock armour layers.

3.4. Underlayer assessment

Since the interaction between the armour layer and its supporting underlayer is fundamental to the performance of single-layer armour systems, the experiments were analyzed with respect to the effect of the underlayer-to-armour nominal diameter ratio ($D_{n50,UL}/D_{n,CL}$). This ratio reflects the relative size of the supporting layer compared with the armour unit and is relevant to placement regularity, interlocking support, underlayer deformation, and filter compatibility. For Coastalock, the underlayer ratio was evaluated together with armour spacing, core permeability, and observed underlayer deformation, rather than as an independent design variable.

For the Coastalock dataset, cases were categorized into different $D_{n50,UL}/D_{n,CL}$ classes, which allowed the effect of underlayer sizing on N_s to be systematically evaluated. Within each class, the associated stability numbers were compared with observed response modes, including stable behaviour, rocking, breathing, underlayer deformation, armour displacement or extraction, and toe-related instability where applicable.

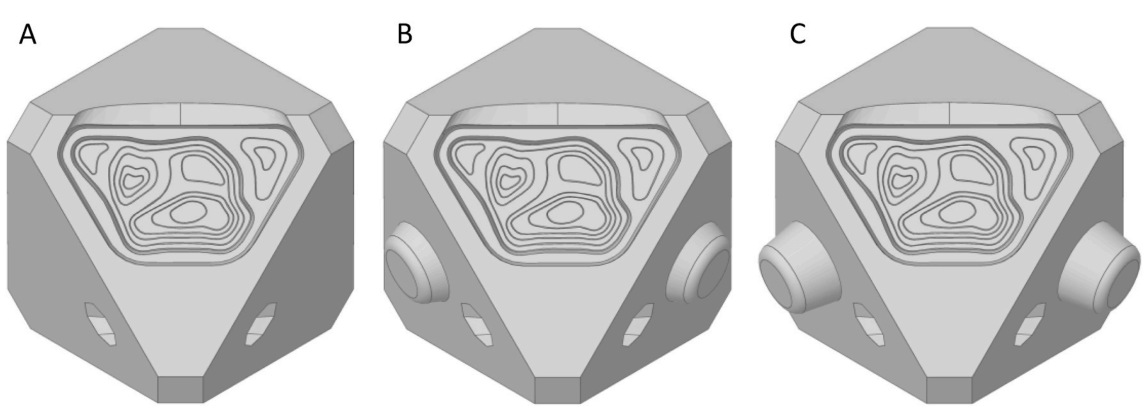

Fig. 5. Coastalock armour units' geometry: (A) standard design, (B) design with protrusions for 10% spacing and (C) design with protrusions for 22.5% spacing.

Table 4
Summary of toe berm configurations tested in Coastalock physical model studies.

Study	Toe rock D_{n50} (m)	Prototype-scale toe rock weight (kg)	Model-scale toe rock weight (kg)	Prototype-scale grading/ grading ratio	Geometry	Surface type beneath the toe
Sayar et al. (2025)	0.72	506	0.150	340-680 kg	3 rocks wide, 2 rocks high	Concrete seabed
Ławniczak (2024)	1.09	1817	0.235	$d_{85}/d_{15} = 1.19$	3 rocks wide, 2 rocks high	Glued rock (rough and smooth)
Baker et al. (2023)	1.42	3973	1.180	3000-5000 kg	2 rocks wide, 1 rock high	Concrete seabed

Table 5
Contextual comparison of tested toe-rock sizes and calculated toe-rock sizes using the van der Meer et al. (1996) toe-stability formula for the critical toe-related conditions. (H_s: significant wave height, h_t: vertical distance from the toe berm to the still water level, h: still water depth).

Study	H_s (m)	h_t (m)	h (m)	Calculated $D_{n50,\ toe}$ (m)	Calculated toe rock weight (kg)	Tested toe rock weight (kg)	Observed toe response
Sayar et al. (2025)	6.58	7.80	9.00	0.58	268	506	Stable seaside toe; lee-side toe damage under severe overtopping
Ławniczak (2024)	6.14	13.31	22.43	0.95	1206	1817	No toe failure observed
Baker et al. (2023)	4.19	4.33	5.50	0.44	115	3973	No toe failure observed

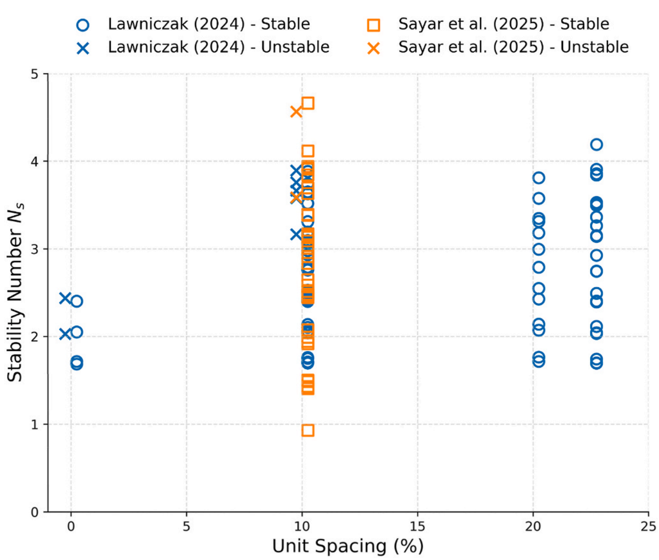

Fig. 6. Stability number (N_s) distribution for Coastalock units placed on permeable-core configurations with different armour-unit spacings. Each marker represents one individual sea-state test run. Stable cases are shown with hollow markers, while unstable cases are indicated with "×" markers. Stable and unstable markers are shifted slightly in opposite horizontal directions for visual clarity.

Because the tested underlayer ratios were not distributed uniformly across all spacings, core types, and wave conditions, underlayer recommendations were interpreted within the specific combinations tested.

3.5. Overtopping analysis

Wave overtopping was analyzed by expressing the mean overtopping discharge in non-dimensional form following (EurOtop, 2018). For each test, the overtopping volumes collected behind the crest of the structure were converted into a mean discharge per unit width, q. These values were then normalized. The resulting non-dimensional overtopping discharge is denoted as q^*, where $q^* = q/\sqrt{gH_s^3}$. This normalization allows direct comparison of the Coastalock measurements with empirical EurOtop prediction curves and provides a consistent framework for assessing overtopping performance.

The influence of the armour unit characteristics was incorporated by calibrating the roughness factor (γ_f) against the (EurOtop, 2018) prediction formula (presented here as Equation (5)) for mean overtopping discharge. For the sloping structures considered in this study, the calibration was performed using the EurOtop formulation relating non-dimensional overtopping discharge to relative freeboard, slope effects, and reduction factors, with γ_f representing the roughness and permeability effect of the Coastalock armour layer.

$$\frac{q}{\sqrt{g \times H_s^3}} = 0.09 \times exp\left(-\left(1.5\frac{R_c}{H_s \times \gamma_{f\times}\gamma_{\beta}}\right)^{1.3}\right) \tag{5}$$

Here, q is the mean overtopping discharge per unit width, R_c is the crest freeboard, H_s is the incident significant wave height, and γ_β represents the obliquity factor. The calibration employed a best-fit optimization, in which γ_f was varied until the error between the measured and predicted non-dimensional discharges was minimized. This approach provided an objective means of identifying representative γ_f values for Coastalock-armoured slopes, ensuring that the experimental data could be consistently expressed within the standard EurOtop methodology. Measured values below $q^* = 5 \times 10^{-5}$ were treated as negligible overtopping and excluded from the γ_f calibration.

3.6. Toe stability assessment

Because the stability of rubble mound armour is strongly related to the design of the toe structure, this element was explicitly included in the Coastalock analysis. Test cases were grouped according to their structure's toe dimensions. The tested toe configurations are summarized in Table 4, while the hydraulic conditions and calculated toe-rock requirements for the most critical cases are summarized in Table 5. Since the dataset contained a single case where instability was attributed to toe failure, this condition was analyzed separately to better understand its underlying causes. For the remaining stable cases, the tested toe rock weights and configurations were systematically compared to the values predicted by the van der Meer et al. (1996) toe stability formula, which has become a standard reference in rubble mound toe design.

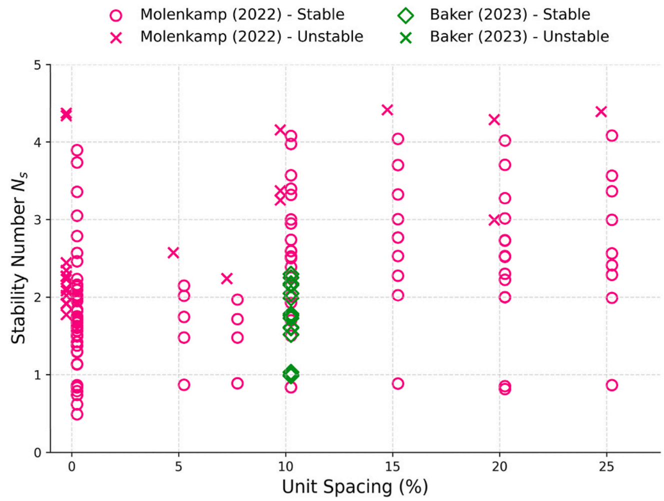

Fig. 7. Stability number (N_s) distribution for standard Coastalock units placed on impermeable-core revetment configurations. Each marker represents one individual sea-state test run. Stable cases are shown with hollow markers, while unstable cases are indicated with "×" markers. Stable and unstable markers are shifted slightly in opposite horizontal directions for visual clarity.

Table 6
Critical or lower-bound stability numbers (N_s) obtained from model tests for San Diego or equivalent configurations, including Mid-Point configurations for protruded Coastalock units (PC: permeable core, IC: impermeable core, PT: Coastalock units with protrusions).

Armour unit spacing (%)	Critical or lower-bound N_s
0 (PC)	1.87
0 (IC)	1.76
5 (IC)	2.36
7.5 (IC)	2.10
10 (PC-PT, Mid-Point)	3.64
10 (IC)	2.92
10 (PC)	3.39
15 (IC)	4.23
20 (PC)	3.81[a]
20 (IC)	4.15
22.5 (PC-PT)	4.19[a]
25 (IC)	4.08

[a] Values reported for configurations without observed armour-layer failure represent the maximum tested stable stability number and should be interpreted as lower-bound estimates of the critical stability number.

Table 7
Preliminary design stability number (N_s) and corresponding Hudson stability coefficient (K_D) for selected spacings (PC: permeable core, IC: impermeable core, PT: Coastalock units with protrusions).

Spacing (%)	Design N_s	Corresponding K_D
10 (PC-PT, Mid-Point)	2.43	9.51
10 (IC)	1.95	4.92
10 (PC)	2.26	7.68
22.5 (PC-PT)	2.79	14.55

The van der Meer et al. (1996) toe-stability formula was applied as shown in Equation (6):

$$\frac{H_s}{\Delta \times D_{n50,toe}} = \left(2 + 6.2\left(\frac{h_t}{h}\right)^{2.7}\right) N_{od}^{\ 0.15} \tag{6}$$

where $Dn_{50,toe}$ is the nominal toe rock diameter, h_t is the vertical distance from the top of the toe berm to the still-water level, h is the water depth at the toe, and N_{od} is the toe damage number. In the present calculations and comparison, $N_{od} = 2$ was adopted to represent moderate acceptable toe damage. For each tested configuration, the calculation was performed using the sea state that produced the largest toe-stability demand, defined by the maximum tested incident wave height combined with the corresponding toe submergence ratio h_t/h.

The tested toe rock weights spanned a range of configurations, and their differences from the calculated values highlighted the influence of experimental design choices on observed performance. In several cases, the tested toe material was heavier than the calculated minimum value because the physical models were designed to maintain a stable toe while evaluating the Coastalock armour layer response. This distinction is important because toe-triggered instability can initiate armour-layer damage without indicating direct instability of the Coastalock units themselves.

4. Hydraulic performance and design interpretations

4.1. Hydraulic stability assessment

The consolidated dataset was examined to identify the primary parameters governing Coastalock stability across all tested configurations. Particular attention was given to armour unit spacing, protrusions, core permeability, underlayer grading, and observed armour-layer response, which consistently influenced the onset of instability.

The stability numbers calculated from the consolidated dataset span a broad range of conditions. The 10% and 22.5% spacing data from Ławniczak (2024) shown in Fig. 6 corresponds to tests conducted with Coastalock units with protrusions, whereas the remaining data in Fig. 6 and all data presented in Fig. 7 represent tests performed with the standard Coastalock geometry.

Figs. 6 and 7 show that Coastalock stability response varied with spacing, protrusions, core permeability, and placement configuration. The permeable-core configurations generally showed reduced uplift-related response compared with impermeable-core configurations, particularly at low spacing, although this comparison should be interpreted within the tested combinations of spacing, underlayer, orientation, toe configuration, and wave conditions. The figures therefore support configuration-specific analysis rather than an isolated comparison of core permeability.

4.1.1. Standard coastalock design

The stability performance of the Coastalock armour layer was expressed in terms of the stability number (N_s), following the conventional approach used in RMBW design practice. The results revealed a distinct threshold behaviour: stable configurations were maintained up to moderate values of N_s, whereas instability emerged once this limit was exceeded, providing a clear benchmark for performance evaluation. For test series in which no failure occurred, the maximum tested N_s was interpreted as a lower-bound estimate of the critical stability condition rather than as the exact failure threshold.

A consistent trend was observed between core type and hydraulic response. For densely placed armour layers with unit spacing lower than 10%, permeable-core structures exhibited higher N_{sc} (critical stability number) than impermeable-core sections, indicating that increased

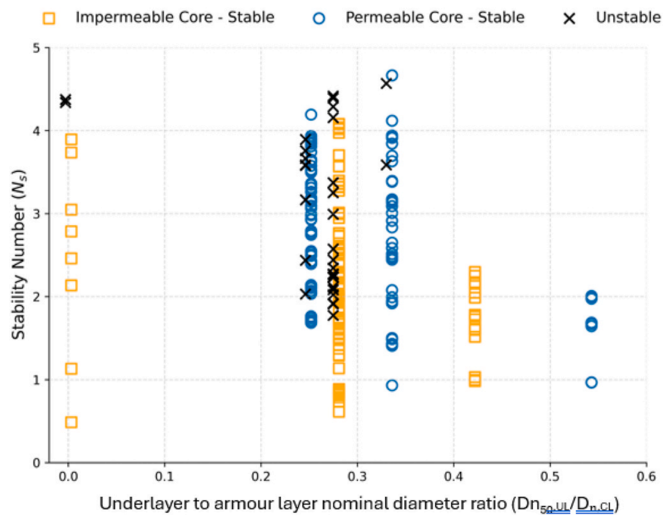

Fig. 8. *Stability number (N_s) versus underlayer to armour layer nominal diameter ratio ($Dn_{50,UL}/D_{n,CL}$) for Coastalock units placed on permeable and impermeable cores. Stable test cases are shown with hollow markers, while unstable cases are indicated with crosses.*

Table 8
Underlayer to armour unit nominal diameter ratio and hydraulic instability occurrence (IC: Impermeable Core, PC: Permeable Core).

$D_{n50,UL}/D_{n,CL}$	Number of test runs resulting in hydraulic instability	Total number of test runs	Instability Occurrence (%)
0.000 (IC)	2	11	18.2
0.278 (IC)	20	121	16.3
0.419 (IC)	0	30	0
0.249 (PC)	8	108	7.4
0.339 (PC)	2	36	5.6

drainage capacity reduces uplift pressure beneath the armour layer and delays the onset of instability. Impermeable cores, in contrast, showed earlier transitions to instability, with reduced capacity for pore pressure dissipation and greater underlayer deformation.

The influence of armour unit spacing and protrusions was similarly pronounced. Among the tested configurations, 22.5% spacing with protrusions provided the highest observed stability margin, while compact placements (<10%) reduced porosity and favoured uplift-driven displacement. Protruded units (PT) demonstrated enhanced interlocking and resistance against rocking or extraction, especially on permeable cores, where improved porosity and fit between adjacent units minimized vertical motion. These trends in stability, as shown in Table 6, indicate that spacing and protrusions exhibit decisive control on Coastalock stability.

The values in Table 6 are configuration-level critical or lower-bound stability numbers, not the minimum stable N_s observed among all individual sea-state runs. For test series where both stable and unstable conditions bracketed failure, the critical N_s was estimated from the transition between the highest stable and lowest unstable conditions. For test series where no armour-layer failure occurred, the maximum tested stable Ns was retained as a lower-bound estimate of the critical condition. Individual stable runs within a sequential test series are therefore not treated as independent failure thresholds.

The stability analysis demonstrated thresholds emerging for the unit spacing effect. To transform these experimental observations into conservative design practice, a safety factor is applied to both stability parameters, as shown in Table 7. The Coastal Engineering Manual (USACE, 2002) and the Rock Manual (CIRIA and CETMEF, 2007) recommend such safety factors when using experimental results for armour layer design, reflecting uncertainties associated with hydraulic variability, construction tolerances, and scale effects. In this study, a safety factor of 1.5 was adopted, corresponding to the common practice of designing for approximately 67% of the experimentally observed critical N_s, thereby providing adequate conservatism in Coastalock stability assessment.

The stability coefficients derived from these results, presented in Table 7, indicate that the preliminary design N_s values for permeable core configurations typically range between 2.2 and 2.8, corresponding to design K_D values of approximately 9–15 for 2V:3H slopes, consistent with the hydraulic performance of established single-layer systems such as Accropode and Xbloc. For the 10% configurations, the design value is based on the lower-bound stability interpretation summarized in Table 6, rather than on the lowest stable sea-state run. Applying the safety factor of 1.5 to Table 6 value of $N_s = 3.39$ gives the preliminary design value $N_s \approx 2.26$. A lower individual stable run within the same sequential loading history is not interpreted as the critical stability threshold.

As an additional conservatism check, a lower-tail statistical estimate was performed on the impermeable core configurations with spacing ≥ 10%. This subset was selected because it represents comparable cases, while also providing multiple independent configurations within a consistent structural configuration. The sample mean and standard deviation are 3.76 and 0.75, respectively. Using a one-sided 5% lower confidence bound based on the Student-t distribution (number of samples is 4, degree of freedom is 3), the conservative estimate of the critical stability number is approximately $N_{s-critical,5\%} \approx 2.88$. This statistical approach was not extended to all configurations due to the limited number of independent cases within other subsets and the heterogeneity in tested configuration arrangements, which would not provide a statistically meaningful estimate. The resulting lower-tail value is consistent with the adopted design stability number obtained by applying the global safety factor of 1.5 to the experimentally observed critical values.

Across the experimental programs, breathing was observed mainly for densely placed armour layers with 0% or low spacing (<10%). Molenkamp (2022) and Ławniczak (2024) reported cyclic uplift and resettlement associated with pore-pressure fluctuations and occasional underlayer deformation, but these responses generally remained localized until extraction or displacement occurred. In the larger-scale emergent RMBW tests of Sayar et al. (2025), no breathing or underlayer deformation was recorded up to $H_s \approx 5.7$ m, indicating stable interlocking under the tested 1:15-scale conditions. Unit extraction was limited to low-spacing configurations, local transition zones, or the upper bound of tested hydraulic loading, whereas configurations with spacing of 10% or greater generally remained stable within the tested envelope.

4.1.2. Coastalock with protrusions

The protruded Coastalock tests evaluated the combined effect of controlled spacing and protruded unit geometry at 10% and 22.5% spacing; therefore, spacing and protrusion effects cannot be isolated from each other in these configurations.

The tests with protrusions indicated that a more porous armour layer and enhanced interlocking provided by the protrusions with 22.5% spacing maintained armour-layer stability with no failure reported throughout the entire set of tests. The structure remained fully stable at the maximum significant wave height that could be produced in the flume, corresponding to a lower-bound critical stability number $N_s = 4.19$ (design $N_s = 2.80$) tested only with protruded units.

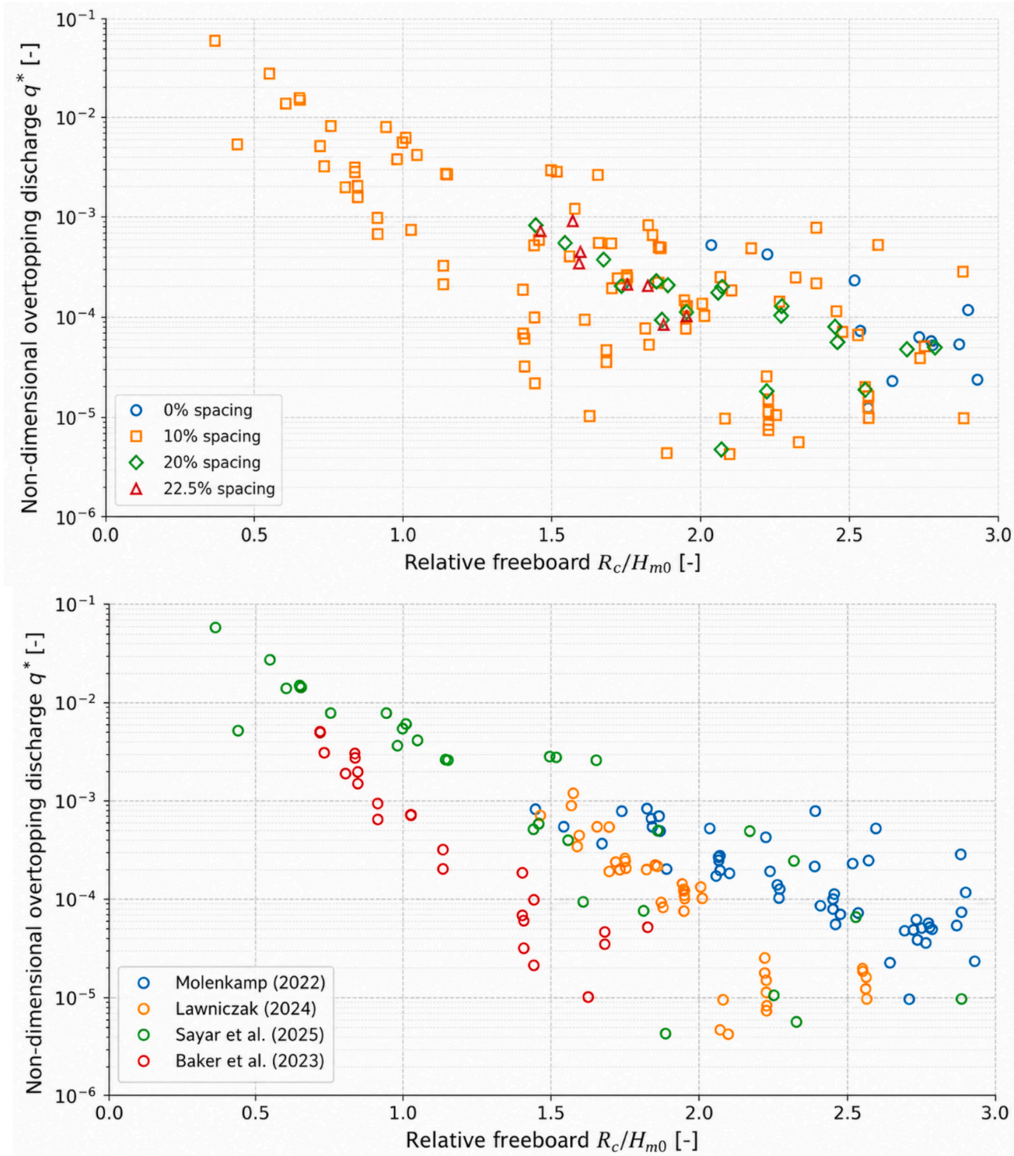

Fig. 9. Non-dimensional overtopping discharge ($q^* = q/\sqrt{gH_s^3}$) for Coastalock-armoured slopes. Each marker represents one test run. Top: comparison of overtopping results for different armour unit spacings as a function of relative freeboard. Bottom: comparison of overtopping results from different experimental studies as a function of relative freeboard (R_c/H_{m0}).

4.2. Underlayer response

The underlayer provides the regular support surface required for single-layer interlocking and resists deformation under wave-induced uplift and run-down forces. Its effect must therefore be interpreted together with armour spacing, core permeability, and placement quality.

Observed damage mechanisms linked instability to underlayer response mainly at low spacings. Molenkamp (2022) and Ławniczak (2024) documented breathing, sliding, and S-shaped settlement when spacings were below 10%, whereas Sayar et al. (2025) showed that a permeable core, regular 10% spacing, and a suitable underlayer prevented these mechanisms under the tested large-scale emergent RMBW conditions.

Sayar et al. (2025) further showed that a coarser underlayer does not necessarily improve stability: larger rock can create an irregular support surface that reduces placement regularity and increases local rocking risk. The underlayer ratio is therefore treated as a coupled parameter, not as a stand-alone stability predictor.

The relationship between underlayer-to-armour nominal diameter ratio and stability response is shown in Fig. 8. The figure compares stable and unstable test runs for permeable- and impermeable-core configurations and supports the interpretation that underlayer response must be evaluated together with spacing, core permeability, and placement regularity.

Results shown in Table 8 indicate that, for permeable-core configurations, instability occurrence decreases as the D_{n50} underlayer to D_n armour layer increases within the tested range. Instability was observed in 7.4% of tests at $D_{n50,UL}/D_{n,CL} \approx 0.249$, reduced to 5.6% at $D_{n50,UL}/D_{n,CL} \approx 0.339$. These results suggest that, within the tested permeable-core configurations, larger underlayer ratios improve resistance to breathing and extraction mechanisms when combined with adequate armour spacing and a permeable core, while no single ratio should be interpreted as an absolute stability threshold. Additionally, core permeability was found to be a dominant parameter, as impermeable-core cases exhibited substantially higher instability occurrence even at comparable underlayer ratios, wave and structural conditions. The absence of instability at the highest tested underlayer ratios should be interpreted

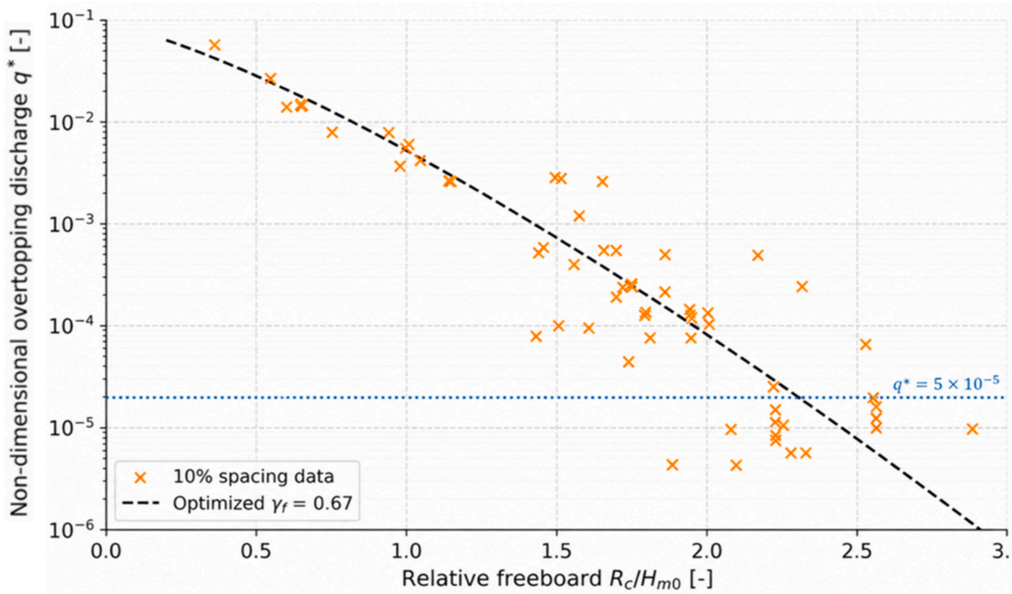

Fig. 10. Non-dimensional overtopping discharge ($q^* = q/\sqrt{gH_s^3}$) plotted against relative freeboard (Rc/Hm0) for the 10% armour unit spacing configuration. The dashed line represents the EurOtop (2018) prediction using $\gamma_f = 0.67$; data with $q^* < 5 \times 10^{-5}$ were excluded from the calibration.

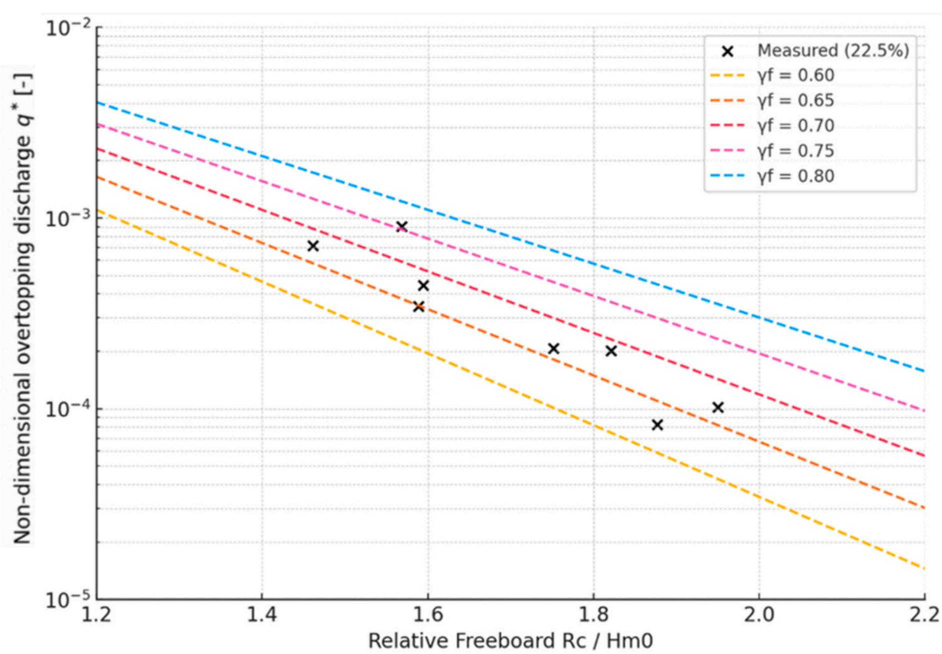

Fig. 11. Non-dimensional overtopping discharge ($q^* = q/\sqrt{gH_s^3}$) plotted against relative freeboard (R_c/H_{m0}) for 22.5% spacing configuration. Dashed lines show the EurOtop (2018) sensitivity range around the representative $\gamma_f = 0.67$ value; data with $q^* < 5 \times 10^{-5}$ were excluded from the calibration.

in relation to the corresponding hydraulic loading conditions, core type, slope geometry, and unit arrangement, rather than as evidence of an unconditional stability threshold.

4.3. Overtopping performance

The overtopping performance of Coastalock-armoured slopes was assessed using the (EurOtop, 2018) framework, with measured overtopping volumes converted into dimensionless mean discharges to allow direct comparison with standard prediction curves. Fig. 9 presents the overtopping data grouped by armour-unit spacing and by experimental campaign. Previous investigations found no consistent spacing- or core-permeability-dependent trend in overtopping rates across the available configurations; therefore, the present analysis uses these groupings descriptively and focuses on calibration of a representative EurOtop roughness factor.

For the 10% spacing configuration, measured mean overtopping discharges align closely with EurOtop (2018) curves; calibration produced a roughness factor of $\gamma_f \approx 0.67$ as shown in Fig. 10, which is higher than the typical values reported for many established single-layer armour units and therefore indicates a lower overtopping-reduction effect within the tested Coastalock configurations. This value is retained as the representative calibrated roughness factor for the tested Coastalock configurations rather than presenting multiple design curves.

Table 9
Qualitative and quantitative synthesis of dominant hydraulic response variables identified from the consolidated Coastalock physical model database.

Variable	Observed influence within the tested data	Design interpretation
Armour unit spacing	Low spacing (<10%) was associated with breathing, underlayer deformation, and occasional extraction. Spacing of 10% or higher generally reduced these response modes within the tested configurations, although performance also depended on protrusions, core permeability, and underlayer support.	Spacing is a primary stability-related design variable. 10% spacing represents the most broadly tested standard-unit configuration, whereas the 22.5% protruded-unit configuration showed the highest tested stability. These spacing recommendations should be interpreted together with core permeability, underlayer support, and placement regularity.
Protrusions	The 22.5% protruded configuration showed no armour-layer failure up to the maximum generated wave condition. The available tests do not isolate the independent effect of spacing from the effect of protruded geometry.	The 22.5% protruded configuration is the best-performing tested geometry, with design Ns ≈ 2.8 and $K_D \approx 15$ for the tested 2V:3H permeable-core configuration. This result should not be generalized to non-protruded 22.5% spacing without additional testing.
Core permeability	Permeable-core configurations were generally associated with reduced uplift- and pore-pressure-related response compared with impermeable-core configurations, particularly at low spacing.	Core permeability should be treated as an important support condition for armour stability, particularly where low spacing may increase uplift and pore-pressure beneath the armour layer.
Underlayer ratio and regularity	Underlayer deformation depended on both underlayer size and armour spacing. Larger underlayer stone size alone did not consistently improve stability, particularly where coarser gradings reduced placement regularity.	For tested permeable-core configurations, $D_{n50,UL}/D_{n,CL} \approx 0.25–0.34$ is a practical preliminary range when combined with adequate spacing and controlled placement; it should not be used as a stand-alone universal rule.
Overtopping/ freeboard	Measured overtopping was analyzed within the EurOtop framework and represented by a calibrated γ_f value for the tested Coastalock-armoured slopes.	Selected $\gamma_f = 0.67$ provides a representative preliminary roughness factor for the tested trunk-section configurations. Lower generic single-layer armour roughness factors should not be adopted without project-specific validation.
Toe configuration	One toe-related instability was observed under severe overtopping and rear-side downrush. Other toe configurations remained stable within the tested conditions, often with toe rock weights exceeding values calculated using conventional toe-stability formulas.	Toe design should be conservative, particularly for overtopped, rear-side-loaded, mobile-bed, or scour-prone configurations where toe displacement could initiate progressive armour-layer damage.

As shown in Fig. 11, the 22.5% spacing tests produced overtopping discharges that align closely with EurOtop (2018) predictions, with calibration indicating γ_f values mostly between 0.65 and 0.70. This range indicates that the 22.5% protruded configuration falls within the calibrated overtopping range observed for the tested Coastalock configurations.

Table 10
Baseline and alternative Coastalock configurations for preliminary hydraulic design.

Parameter	Baseline tested configuration	Standard unit alternative configuration
Armour unit spacing (%)	22.5	10
Armour unit type	with Protrusions	Standard
Core type	Permeable	Permeable
Front slope	2V:3H	2V:3H
$D_{n50,\ underlayer}\ /\ D_{n,CL}$	0.34	0.25–0.34
Critical stability basis	No failure observed up to $N_s = 4.19$; lower-bound critical condition	Comparable stability observed across multiple campaigns; critical $N_s \approx 3.39$
Design stability number, N_s	2.80	2.26
Hudson coefficient (K_D) for 2V:3H slope	14.6	7.68
Primary interpretation	Best-performing tested configuration	Most broadly tested standard-unit configuration

4.4. Toe and rear side response

In Coastalock-armoured slopes, as in other single-layer armour unit systems, the toe plays a critical role in stability by providing support to the first rows of the armour, resisting scour and settlement, and preventing slope failure triggered at the base. Across the experimental series, only one toe-related instability was observed during the large-scale experiments of Sayar et al. (2025), occurring at the lee side of the emergent breakwater structure under severe overtopping volumes that exceeded the suggested limits in EurOtop (2018). The overtopping downrush and localized wave forces damaged the leeward toe, dislodging the bottom toe armour row and triggering subsequent slope failure. Once the leeward toe was reinforced, no failure of the toe was registered under the same wave and overtopping conditions.

These findings highlight the critical role of toe stability in Coastalock design, as failure initiated at the toe can compromise the entire armour slope; ensuring conservative toe design and sizing remains essential. The remaining toe configurations did not fail under the applied loading, but this outcome should be interpreted in relation to the tested toe geometries, rock sizes, and, in several cases, toe weights exceeding values calculated using conventional rubble mound toe stability formulas.

The observed rear-side damage is therefore interpreted as a toe-instability mechanism under severe overtopping rather than as a generalized rear-slope armour stability criterion. For configurations involving substantial overtopping, mobile beds, scour-prone toes, or site-specific rear-slope loading, toe stability should be verified using conservative design assumptions or additional physical modelling.

4.5. Synthesis of controlling hydraulic response variables

The consolidated dataset includes multiple structural and hydraulic variables, and not all combinations were tested systematically. A fully general multivariate stability formula is therefore not derived from the available data. Instead, the observed response patterns identify the parameters that most consistently controlled armour-layer behaviour within the tested envelope. The synthesis in Table 9 is therefore qualitative and configuration-specific while the baseline tested configuration and standard-unit alternative retained for preliminary hydraulic design are summarized in Table 10.

5. Preliminary design recommendations and application limits

The design recommendations in this section are intended for preliminary design of Coastalock-armoured straight trunk sections within the tested experimental envelope. They distinguish between the best-performing tested configuration, the most broadly tested standard-unit alternative, and configurations requiring project-specific verification as summarized in Table 10.

5.1. Baseline tested configuration and design values

The best-performing tested configuration for Coastalock design is defined by tests on a permeable core with a 2V:3H slope, 22.5% unit spacing with protrusions, and an underlayer-to-armour size ratio of 0.34. Under these conditions, the armour remained fully stable under all wave conditions achievable within the laboratory. The maximum tested stability number was $N_s = 4.19$. Since no failure occurred, this value represents a lower bound of the critical stability number ($N_{sc} > 4.19$) rather than an experimentally interpolated failure threshold. Applying a global safety factor of 1.5 to this lower-bound estimate results in a conservative design $N_s \approx 2.8$.

The baseline configuration performed within the upper range of reported stability constants for established single-layer systems. This interpretation is limited to the tested slope height, protruded geometry, permeable core, and 2V:3H slope, and should not be generalized to other structural arrangements without verification.

It should also be noted that the 22.5% spacing configuration was tested exclusively with Coastalock units with protrusions. No corresponding tests without protrusions were conducted at this spacing. Therefore, the observed performance at 22.5% spacing cannot be directly attributed to spacing alone, nor can the independent contribution of protrusions be isolated. The conclusions for this configuration are thus limited to the tested geometry.

The standard Coastalock unit at 10% spacing on a permeable core remains the most broadly tested standard-unit alternative in the available dataset. Although its stability margin (design $N_s \approx 2.26$) is lower than that of the 22.5% protruded configuration, it was tested across multiple campaigns and therefore provides the broader basis for standard-unit preliminary design within the tested envelope.

5.2. Underlayer design

The test results indicate that Coastalock stability is influenced by the underlayer ratio $D_{n50,UL}/D_{n,CL}$, but this parameter should not be interpreted independently from armour porosity, core permeability, and placement regularity. For permeable-core configurations, instability occurrence decreased within the tested underlayer-ratio range, and $D_{n50,UL}/D_{n,CL}$ values of approximately 0.25–0.34 were associated with limited instability when combined with adequate armour spacing, a permeable core, and controlled unit placement. No instability was observed for higher-ratio cases within the available data; however, these cases were not systematically tested under the most severe hydraulic loading conditions and should therefore not be interpreted as defining an absolute stability threshold. Excessively large underlayer stones may also reduce support regularity and locally increase rocking or instability risk. Therefore, $D_{n50,UL}/D_{n,CL} = 0.25–0.34$ is proposed as a practical preliminary range for the tested permeable-core applications, rather than as a stand-alone or universally applicable underlayer design rule.

5.3. Overtopping design

For preliminary overtopping calculations of Coastalock-armoured slopes within the tested range, the EurOtop (2018) formulation may be applied using a preliminary roughness factor $\gamma_f = 0.67$. This value is consistent with the best-fit calibration of the available overtopping data and lies within the primary range obtained from the analyzed configurations ($\gamma_f \approx 0.65–0.70$).

The recommended γ_f value should be interpreted as a hydraulic roughness parameter for the tested Coastalock trunk-section configurations and not as a universal value for all possible slopes, crest geometries, armour orientations, or low-crested/overtopped arrangements. Where overtopping is a governing design condition, project-specific checks should consider crest freeboard, crest width, rear-side drainage, and the potential interaction between overtopping downrush and rear toe stability.

5.4. Toe and rear-side response

Toe stability was identified as a significant factor for the Coastalock armour layer. The only recorded toe failure in the test campaigns was reported at the lee side of the structure and linked to toe instability under heavy overtopping. Evaluation against van der Meer et al. (1996) toe stability formula showed that conservative toe rock weights, often greater than the calculated values, contributed to overall slope robustness. Accordingly, established rubble mound toe stability methods should be used as a minimum design check for Coastalock-armoured slopes, with additional conservatism where toe displacement could initiate progressive armour-layer instability.

On the rear side, armour stability was fully maintained as long as the toe remained intact, but excessive overtopping volumes proved capable of weakening the rear toe stability and initiating slope damage. These observations should be interpreted primarily as toe-design evidence under overtopping-induced loading rather than as a general rear-slope armour recommendation independent of toe support. It is therefore advised that designers apply conservative toe sizing, particularly for rear-side protection with moderate to heavy overtopping rates in highly exposed sites.

5.5. Application limits

The present recommendations apply only to straight, two-dimensional trunk sections within the tested structural and hydraulic envelope. The available data cover front slopes of 2V:3H and 1V:2H.

The design recommendations are based on tests covering spacings from 0 to 25%, of which 10% and 22.5% are the principal configurations retained for preliminary design interpretation. In terms of orientation, San Diego (without protrusions) and cavity-forward arrangements were the most broadly represented orientations in the available dataset, whereas designs employing cavity-sideways and downward orientations were more limited and therefore additional model testing is suggested. The 22.5% spacing recommendation is further limited to Coastalock units with protrusions, since no equivalent 22.5% spacing tests were conducted using the standard unit geometry.

The stability results are based on test durations that varied among the source campaigns, with many test runs containing approximately 1,000–1,200 waves, while some runs were shorter because of failure, test-sequence constraints, or facility-specific procedures. These tests support interpretation of short-term storm response, but long-term exposure and lifetime performance of Coastalock armour layers still require prototype monitoring or additional testing.

In practice, several site-specific factors can increase hydrodynamic demand or reduce stability margin. Additional physical modelling is recommended for roundheads, curved alignments, transitions, oblique wave attack, currents, mobile beds, severe plunging or depth-limited breaking at the toe, different unit sizes, alternative protrusion geometries, extended storm durations, and configurations in which biological growth or sediment infill may substantially alter armour-layer porosity. Toe and rear-side observations from the present dataset are configuration-specific and should not be interpreted as independently calibrated toe-stability guidance.

6. Discussion

This study consolidates results from four independent physical modelling programs, yielding the first unified dataset for the hydraulic stability and performance of Coastalock armour units. By integrating 306 individual test runs, the research establishes a coherent framework for developing preliminary hydraulic design recommendations.

Coastalock achieved a design $N_s = 2.8$ ($K_D \approx 15$) for the best-performing tested 2V:3H trunk-section configuration with protruded units at 22.5% spacing on a permeable core, while the tested 10% spacing Coastalock configuration provided a lower preliminary design value of $N_s = 2.26$ ($K_D \approx 7.68$). Both values fall within, the general design range of N_s = 2.0–3.0 commonly reported for single-layer armour systems. For overtopping calculations, the available data support use of the EurOtop framework with a representative calibrated roughness factor of $\gamma_f = 0.67$ for the tested Coastalock trunk-section configurations. This value is higher than the typical values reported for many established single-layer concrete armour units, indicating that lower generic roughness factors should not be adopted for Coastalock without project-specific validation.

The interpretation of the stability results requires attention to the heterogeneous nature of the merged database. The test campaigns differed in core permeability, water depth, slope, toe configuration, underlayer grading, unit spacing, orientation, and the use of protrusions. Accordingly, the available data support configuration-specific design values and sensitivity-based interpretation rather than a universal empirical stability formula for all Coastalock applications. The highest observed armour-layer stability was obtained for the 22.5% spacing configuration with protrusions, while the standard 10% spacing configuration remains the most broadly tested alternative because it was tested across multiple campaigns. The 22.5% result should therefore be interpreted as the performance of the tested protruded geometry, whereas the 10% spacing result provides a broader basis for standard-unit applications within the tested envelope.

The results show that Coastalock stability is governed by the interaction among armour spacing, core permeability, underlayer support, placement regularity, and toe/rear-side boundary conditions. Consequently, underlayer ratios and toe observations should not be interpreted independently from the tested structural configuration.

Although Coastalock incorporates ecological design features, the present study evaluates hydraulic performance only; ecological functionality is retained as unit-design context and was assessed separately for existing Coastalock applications during several biological monitoring campaigns (ECOncrete, 2024; Gutiérrez Martínez et al., 2023; Rella et al., 2024; Sayar et al., 2025).

The proposed recommendations should be used within the application limits defined for the tested two-dimensional trunk-section configurations. The database provides a practical basis for preliminary design, but additional physical modelling remains necessary for configurations outside the tested envelope, including roundheads, curved alignments, oblique wave attack, mobile beds, severe depth-limited breaking, alternative protrusion geometries, and long-duration prototype storm sequences. Within these limits, the study provides a data-supported basis for preliminary Coastalock design while maintaining the need for project-specific verification under more complex site conditions.

7. Conclusions

This work presents the first consolidated preliminary hydraulic design recommendations for the Coastalock armour unit, derived from four physical model investigations and focused on armour-layer stability, underlayer response, overtopping, and toe berm stability for the tested two-dimensional trunk-section configurations.

The consolidated database comprises 306 individual sea-state test runs from four experimental campaigns. The database provides a broad experimental basis for identifying the main parameters controlling Coastalock performance within the tested ranges.

The best-performing tested configuration consisted of Coastalock units with protrusions placed at 22.5% spacing on a permeable core with a 2V:3H slope. No armour-layer failure was observed for this configuration up to the maximum tested stability number, $N_s = 4.19$, which should be interpreted as a lower-bound estimate of the critical stability condition. Applying the adopted safety factor gives a design stability number of approximately $N_s = 2.8$, with a corresponding Hudson coefficient close to $K_D = 15$ for the tested 2V:3H slope.

The standard Coastalock configuration placed at 10% spacing on a permeable core remains a broadly tested alternative, with a design stability number of approximately $N_s = 2.26$ and a corresponding $K_D \approx 7.68$ for the tested 2V:3H slope. Although lower than the 22.5% protruded configuration, this standard-unit configuration was examined across multiple experimental campaigns and provides the broader basis for standard-unit preliminary design within the tested envelope.

The underlayer assessment indicates that Coastalock stability depends on the combined effects of armour spacing, core permeability, underlayer size, and placement regularity. Within the tested permeable-core configurations, $D_{n50,UL}/D_{n,CL}$ values in the approximate range of 0.25–0.34 were associated with stable or limited-instability behaviour when combined with adequate armour spacing and controlled placement. This range should be interpreted as a tested preliminary range rather than a universal underlayer rule independent of other structural parameters.

For overtopping calculations, the EurOtop-based calibration supports $\gamma_f = 0.67$ as a representative roughness factor for preliminary assessment within the tested conditions. Toe and rear-side observations indicate that toe support can influence armour-layer integrity under heavy overtopping and downrush; however, these observations are configuration-specific and should be used as design context rather than general Coastalock-specific toe-stability guidance.

The recommendations are limited to the tested two-dimensional trunk sections, slopes, unit orientations, spacings, underlayer gradations, core conditions, and wave-loading ranges. Additional physical modelling is required before extrapolating the proposed values to roundheads, curved transitions, oblique wave attack, severe depth-limited breaking, different unit sizes, different slopes, non-protruded 22.5% spacing, or long-duration prototype storm sequences. Although Coastalock retains its eco-engineered design intent, the hydraulic design recommendations presented here are governed by hydraulic stability, overtopping, underlayer, and toe and rear side response observations.

For sites involving large tidal variability, substantial biological growth or sediment infill, severe breaking, complex three-dimensional geometry, or long-duration loading, the preliminary values presented here should be used conservatively and verified through project-specific assessment or additional physical modelling.

CRediT authorship contribution statement

Serim Dogac Sayar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jorge Gutiérrez Martínez:** Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Scott Baker:** Data curation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Ioan Nistor:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Yaeli Rosenberg:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing. **Bas Hofland:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **Jeroen van den Bos:** Writing – review & editing. **Fernando Colom Jover:** Validation, Writing – review & editing. **Stefano Kerr:** Data curation, Validation, Writing – review & editing. **Aron Lawniczak:** Writing – review & editing. **Auke Molenkamp:** Writing – review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.coastaleng.2026.105143.

Data availability

Data supporting this study are provided in the article and Supplementary Material, including row-level Coastalock test-run data in Table S1.

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