Regular Research Article

Probabilistic Evaluation of Seawall Performance Against Wave Run-Up and Overtopping Under Variable Water Levels at Serui Fuel Terminal

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Abstract: Seawalls are one of the coastal protection structures commonly used to reduce the risk of wave overtopping, especially in critical coastal infrastructure. At the Fuel Terminal in Serui, overtopping events have been recorded causing damage to several facilities, even under moderate wave conditions. This study evaluates the performance of the existing seawall under the combined influence of probabilistic waves ($H_{2\%}$, $H_{10\%}$, $H_{33\%}$) and sea level variations (MSL and HWL). A 20-year wave dataset (2002–2021) obtained from ECMWF was statistically analyzed, followed by theoretical wave transformation toward the shoreline. Wave run-up was calculated based on the Iribarren-type formulation and empirical equations, in which the 2% exceedance run-up ($R_{2\%}$) was estimated using the probabilistic extreme wave height ($H_{2\%}$) following established empirical correlations for smooth seawalls. Overtopping discharge was estimated using an exponential formula and compared with established overtopping impact classifications. Results indicate that under High Water Level (HWL) conditions, all run-up values exceeded the seawall crest elevation (+1.93 m relative to MSL), with $R_{2\%}$ reaching 3.3 m and a maximum overtopping discharge of 92 l/s/m, corresponding to a high functional damage risk. Wave overtopping does not compromise the structural integrity of the seawall but can cause significant functional damage to facilities and operation behind the wall. Even under MSL conditions, overtopping still occurred for extreme wave conditions ($H_{2\%}$), These results are consistent with field observations in 2020, confirming that the existing seawall geometry and smooth surface contribute to limited wave energy dissipation. Unlike conventional deterministic assessments, this study introduces a probabilistic and field-validated evaluation framework that integrates run-up and overtopping analysis under varying water levels, providing a more realistic basis for assessing seawall performance for future adaptive redesign strategies.

Keywords: Seawall; Wave Overtopping; Wave Run-up; Probabilistic Waves; Water Level Variation; Iribarren Number.

1. Introduction

Seawalls are among the most widely used coastal protection structures designed to reduce the risk of wave overtopping, particularly for critical coastal facilities such as fuel terminals, ports, and other shoreline infrastructure. However, many existing seawalls have been reported to experience overtopping even under moderate wave conditions, indicating that their designs may not have adequately accounted for probabilistic wave characteristics and tidal fluctuations. Wave structure interactions along the coastline are strongly influenced by local

bathymetry and coastal morphology, which affect wave transformation as waves propagate toward the shoreline [1]. This transformation can lead to a concentration of wave energy in shallow areas, increasing local wave heights and, consequently, the potential for overtopping near the structure.

Wave overtopping occurs when the wave run-up exceeds the crest elevation of a coastal structure. Empirical [2] and semi-empirical [3] formulations have been proposed to estimate wave run-up and overtopping discharge on smooth and rough slopes, which have been widely applied in coastal engineering practice to assess seawall safety and performance. The Iribarren number (Ir), representing the relationship between structural slope, wave steepness, and surf similarity, has been identified as a key parameter influencing seawall effectiveness in dissipating wave energy [4][5]. However, the effectiveness of vertical or steep-sloped seawalls tends to decrease with increasing Iribarren numbers, as demonstrated by both laboratory and numerical studies [6][7].

At the Serui Fuel Terminal, overtopping events have been visually documented and analyzed [8]. These incidents caused damage to several nearby facilities, even under moderate wave conditions. The existing seawall at the site is a smooth, near-vertical concrete wall with a crest elevation of +1.93 m above mean sea level (MSL). Field observations and previous analyses indicate that the structure may not have been designed by considering probabilistic wave conditions and water level variations, resulting in insufficient protection against overtopping. Similar conditions have also been reported for other coastal structures designed using deterministic parameters, which often underestimate the combined effects of waves and tides [9].

Overtopping risk is influenced by several interacting parameters, including wave height, run-up, and variations in sea level elevation. When high waves coincide with high water levels, the probability of overtopping increases significantly. Therefore, evaluating seawall performance should consider both probabilistic wave behavior and tidal variations. In this study, a 20-year wave dataset (2002–2021) [10] was used as the basis for deriving probabilistic wave heights ($H_{2\%}$, $H_{10\%}$, $H_{33\%}$) and analyzing their transformation toward the nearshore area.

As waves propagate from deep water toward the coast, they undergo several transformation processes that alter their height, velocity, and direction. These include wave shoaling, refraction, diffraction, and reflection before eventually breaking near the shoreline [11]. Understanding wave transformation, particularly refraction and diffraction, is crucial in the planning and design of coastal and harbor structures [12]. Waves orthogonal tend to bend due to refraction, causing originally parallel wave paths in deep water to become convergent or divergent as they approach shallower regions. This convergence and divergence lead to corresponding increases or decreases in local wave energy and height [1]. The propagation pattern of these orthogonal can be visualized using the *wave crest method* [13], which illustrates wave transformation along the coastal profile. In this study, probabilistic wave conditions derived from deep water were transformed toward the nearshore region through these processes to evaluate the incident wave characteristics acting on the seawall prior to the run-up and overtopping analyses.

Wave run-up was calculated using the Iribarren-type formulation and empirical equations, while overtopping discharge was assessed using the exponential relationship [9]. In this study, probabilistic wave heights ($H_{2\%}$, $H_{10\%}$, and $H_{33\%}$) were used as representative wave inputs to estimate run-up under extreme conditions. Although $R_{2\%}$ is theoretically defined as the run-up level exceeded by 2% of incident waves [14], using $H_{2\%}$ as input provides a physically consistent estimate of extreme run-up for practical design evaluation. The calculated $R_{2\%}$ values were found to be in good agreement with field observation and the empirical relationship [2], confirming the validity of this probabilistic approach for smooth concrete seawalls. The calculated overtopping discharge was then classified according to overtopping impact categories proposed by previous researchers [3][9].

This integrated analytical approach

provides a comprehensive evaluation of seawall performance under realistic hydrodynamic conditions and allows the identification of structural vulnerabilities when exposed to combined wave and tidal forcing. Unlike conventional deterministic approaches that rely on single design wave parameters, this study adopts a probabilistic framework by integrating long-term wave statistics, wave transformation processes, run-up estimation, and overtopping analysis under variable water level conditions. In addition, the analytical results are validated using documented field observations, providing a more realistic assessment of seawall performance under extreme conditions. The objective of this study is to assess the effectiveness of the existing seawall at the Serui Fuel Terminal in mitigating overtopping risk due to the combined influence of probabilistic wave run-up and variations in sea level elevation. The findings of this research are expected to validate theoretical and empirical approaches for assessing wave overtopping and to serve as a technical reference for redesigning and improving coastal protection structures that are more adaptive to extreme probabilistic conditions.

2. Materials and Methods

The methodological framework of this study comprises four main steps: (1) derivation of probabilistic deep-water wave heights ($H_{2\%}$, $H_{10\%}$, and $H_{33\%}$), (2) theoretical transformation of deep-water waves toward the nearshore zone, (3) estimation of wave run-up based on the Iribarren number, and (4) calculation of overtopping discharge under different sea-level conditions, namely mean sea level (MSL) and High Water Level (HWL).

Deep-water wave data from ECMWF covering a 20-year period (2002–2021) [10] were used to derive $H_{2\%}$, $H_{10\%}$, and $H_{33\%}$. Tidal elevation data (HWL, MSL), structural profiles, and overtopping documentation were obtained from previous studies [8]. Deep-water waves were theoretically transformed into nearshore waves using linear wave theory as shown in Equation (1).

$$H'_0 = H_0 . K_s . K_r \qquad (1)$$

Wave orthogonal were then constructed to visualize the propagation and directional transformation of waves from deep water toward the nearshore region. This process allows identification of areas where wave energy becomes concentrated (convergence) or dissipated (divergence) due to refraction effects. The orthogonal was developed using the wave crest method [13], in which lines perpendicular to successive wave crests represent the direction of wave propagation. As waves approach shallower depths, their celerity decreases and wave fronts bend according to Snell's Law, causing the orthogonal to converge or diverge depending on local bathymetric gradients [1]. The resulting orthogonal diagram provides a graphical representation of the refracted wave field and assists in determining the effective incident wave angle and wave height distribution along the seawall.
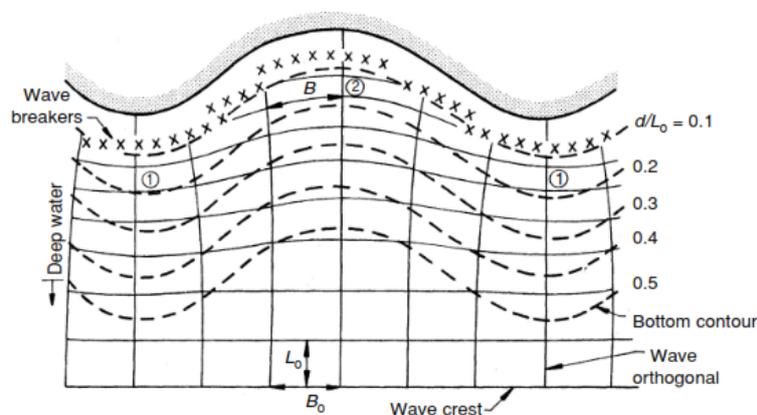

Figure 1. Wave Refraction Pattern [1]

When waves strike the seawall, an upward rush of water occurs along the surface, a process known as wave run-up. This run-up represents one of the most important variables that must be considered in the design of coastal protection structures [15], as it governs the likelihood of wave overtopping and the hydraulic stability of the wall. The vertical wave run-up height is influenced by several factors, including surface roughness (which depends on wall material), slope angle (θ), wave height (H), and wavelength (L). These parameters are represented by the Iribarren number (Ir), which characterizes the relationship between wall geometry and incident wave steepness.

Several previous studies have developed empirical and theoretical approaches to estimate run-up heights. A graphical relationship between wave parameters and run-up magnitude that has been widely adopted for practical design in Indonesia was proposed [4]. It was further emphasized that when waves approach from multiple directions, the combined interaction can significantly affect run-up behavior[15], [16]. Moreover, the effectiveness of overtopping reduction decreases as the Iribarren number increases [5]. The Iribarren number defined as:

$$Ir = \frac{tg\theta}{(\frac{H}{L_0})^{0.5}} \tag{2}$$

Where θ is the slope angle of the seawall, H is the incident wave height, and L_o is the deep-water wavelength. This relationship forms the basis for calculating wave run-up in the present study.

The Ir value obtained from each wave condition was used to determine run-up based on empirical formulations and graphs. Previous empirical studies on smooth and near-vertical seawalls have shown a strong correlation between extreme incident wave heights and the corresponding 2% exceedance run-up level. For smooth concrete surfaces, this relationship is commonly expressed as $R_{2\%} \approx (2.5 - 3.0) H$ or presented in equation (3) where H is wave height and r_f is roughness factor [2]. This relationship indicates that extreme run-up is directly governed by extreme wave conditions. Based on this established correlation, the probabilistic extreme wave height $H_{2\%}$ is adopted in this study as the representative input parameter for estimating $R_{2\%}$. Overtopping discharge was subsequently estimated using Owen's exponential formulation [3], as presented in Equation (4). Here, q is the specific overtopping discharge (m³/s/m), while Q represents the nondimensional overtopping discharge

$$\frac{R_{2\%}}{H} = 3r_f \tag{3}$$

$$Q = \frac{q}{\sqrt{gH^3}} = 0.2exp(-2.6\frac{R_c}{H}\frac{1}{r_f}) \tag{4}$$
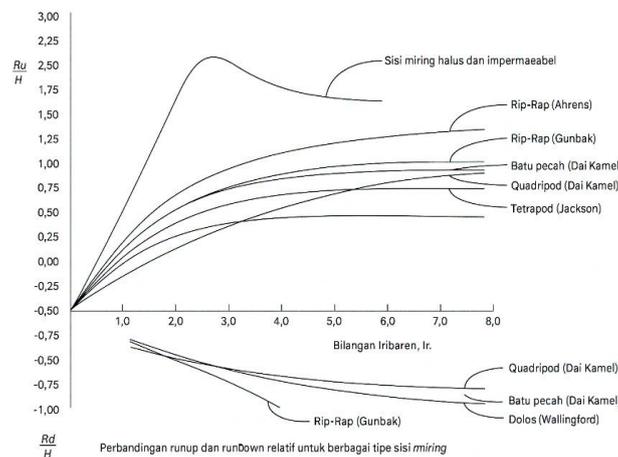

Perbandingan runup dan runDown relatif untuk berbagai tipe sisi *miring*

Figure 2. Relationship between wave run-up and run-down on a coastal slope [4]

Finally, the computed overtopping discharge (*q*) was compared with the established overtopping impact classification limits [9] to evaluate tolerance thresholds and assess the potential risk of structural or facility damage due to wave overtopping.

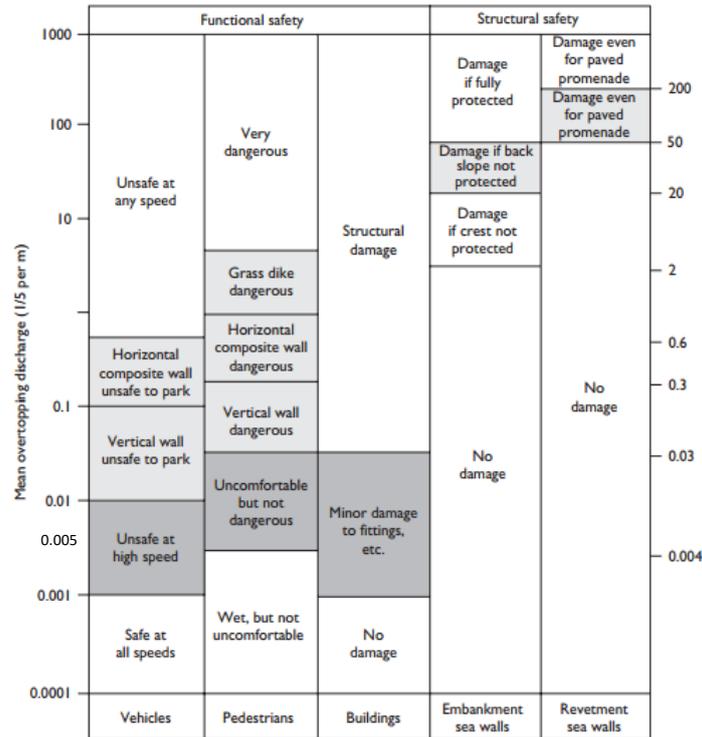Figure 3. Overtopping discharge classification [9]

3. Results

3.1 Field Observation and Existing Seawall Condition

Wave overtopping was visually documented at the Serui Fuel Terminal, as shown in Figure 3 and Figure 4, where waves exceeded the seawall crest and caused damage to several nearby facilities. The existing structure is a massive smooth-surfaced concrete seawall with an almost vertical slope and a crest elevation of +1.93 m from mean sea level (MSL). The physical characteristics of the structure directly affect the way waves interact upon reaching the coastline.

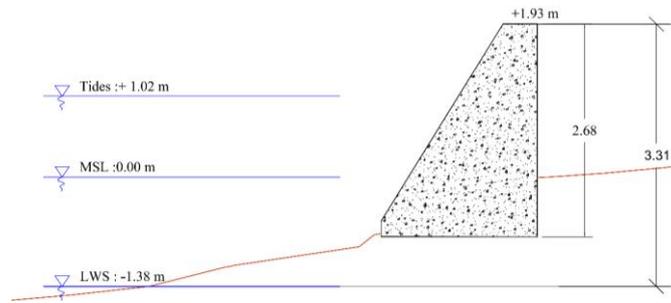Figure 3. Condition of the existing seawall structure [8]

Figure 4. Existing concrete seawall [8]

3.2 Wave Transformation and Orthogonal

As waves propagate from deep water toward the coast, they experience refraction due to seabed depth variations. This process causes the initial parallel orthogonal to become convergent or divergent in shallow regions. Convergent orthogonal results in the concentration of wave energy, which locally increases wave height in front of the seawall [1].

When the nearshore depth in front of the structure is relatively greater than the surrounding area, waves tend not to break before reaching the wall, thus maintaining high energy and increasing overtopping potential. To analyze the spatial distribution of wave energy, wave orthogonal were constructed using the wave crest method [13]. This method visualizes wave transformation from deep water toward the coast for probabilistic wave conditions ($H_{2\%}$, $H_{10\%}$, and $H_{33\%}$), resulting in transformed nearshore wave heights $H'_{2\%}$, $H'_{10\%}$, and $H'_{33\%}$. These transformed wave heights were then used as parameters for the subsequent run-up calculations.

Figure 5. Wave orthogonal propagation pattern near the Serui seawall

3.3 Wave Run-up Calculation Results

Wave run-up was calculated based on the Iribarren number and verified using empirical relationships for smooth slopes [2]. Table 1 presents the calculated run-up results under probabilistic wave conditions.

Table 1. Wave run-up calculation results

Orthogonal	$H_{2\%}$	Lo	tan θ	Ir	Ru/H	$H'_{2\%}$	$Ru_{2\%}$
A			0.63	2.72	2.95	1.11	3.28
B	1.36	21.07	0.63	2.81	2.95	1.05	3.09
C			0.63	2.67	2.95	1.16	3.41
D			0.63	2.62	2.85	1.20	3.42
Average						1.1	3.3
Orthogonal	$H_{10\%}$	Lo	tan θ	Ir	Ru/H	$H'_{10\%}$	$Ru_{10\%}$
A			0.63	3.25	2.25	0.78	1.75
B	1.02	21.07	0.63	3.35	2.10	0.73	1.54
C			0.63	3.19	2.38	0.81	1.93

Orthogonal	$H_{2\%}$	Lo	tan θ	Ir	Ru/H	$H'_{2\%}$	$Ru_{2\%}$
D			0.63	3.13	2.60	0.84	2.19
Average						0.8	1.9
Orthogonal	$H_{33\%}$	Lo	tan θ	Ir	Ru/H	$H'_{33\%}$	$Ru_{33\%}$
A			0.63	3.79	2.10	0.57	1.21
B			0.63	3.91	2.10	0.54	1.13
C	0.80	21.07	0.63	3.71	2.14	0.60	1.28
D			0.63	3.63	2.15	0.62	1.34
Average						0.6	1.2

Based on the results, the calculated run-up values for the transformed probabilistic waves ($H'_{2\%}$, $H'_{10\%}$, and $H'_{33\%}$) were 3.3 m, 1.9 m, and 1.2 m, respectively. The comparison between analytical and empirical results demonstrates a strong consistency, confirming the validity of the applied approach. For instance, at $H'_{2\%}$ = 1.1 m, the computed run-up ($R_{2\%}$) = 3.3 m, resulting in R/H = 3.0 consistent with empirical approximation for smooth surfaces [2]. Figures 6 and 7 illustrate the run-up elevations relative to seawall crest height under MSL and HWL conditions.
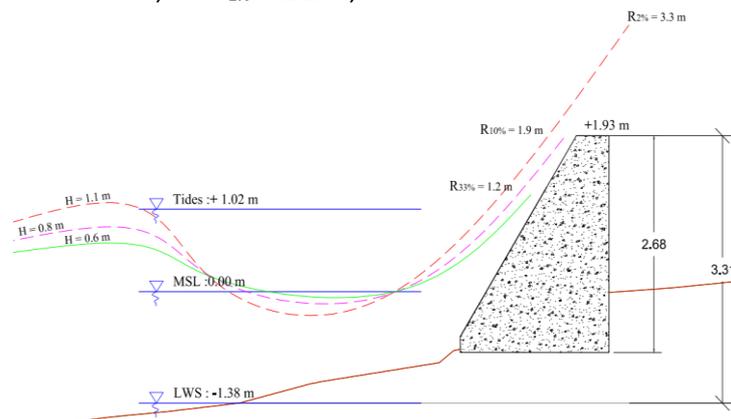

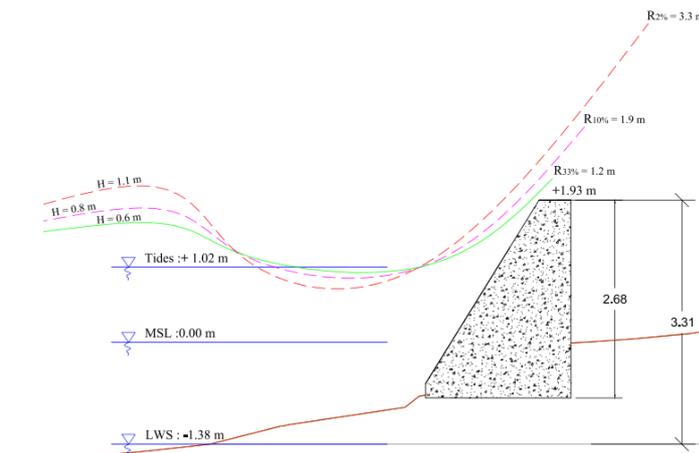Figure 6. Wave run-up under mean sea level (MSL) condition

Figure 7. Wave run-up under high sea level (HWL) condition

3.4 Overtopping Discharge Result

Overtopping discharge was calculated using exponential formula [9] for both MSL and HWL conditions. The results are presented in Tables 2 and 3.

Table 2. Overtopping discharge under MSL condition (l/s/m)

H		Rc	rf	Q	q
$H'_{2\%}$	1.1	1.93	1	0.002	8.8
$H'_{10\%}$	0.8	1.93	1	0.000	0.8

H'33%	0.6	1.93	1	0.000	0.1

	H	Rc	rf	Q	q
H'2%	1.1	0.91	1	0.025	92
H'10%	0.8	0.91	1	0.010	22
H'33%	0.6	0.91	1	0.003	5

Under MSL conditions, overtopping discharges (q) for H'2%, H'10%, and H'33% were 8.8, 0.8, and 0.1 l/s/m, respectively. These values indicate that even under average tidal levels, wave overtopping can still occur during extreme wave events ((H'2%), potentially causing minor to moderate damage to facilities around the terminal area.

Under HWL conditions, overtopping discharge increased significantly with (q) for (q) for H'2%, H'10%, and H'33% reached 92, 22 and 5 l/s/m. Indicating a high-risk damage to buildings and infrastructure around seawall.

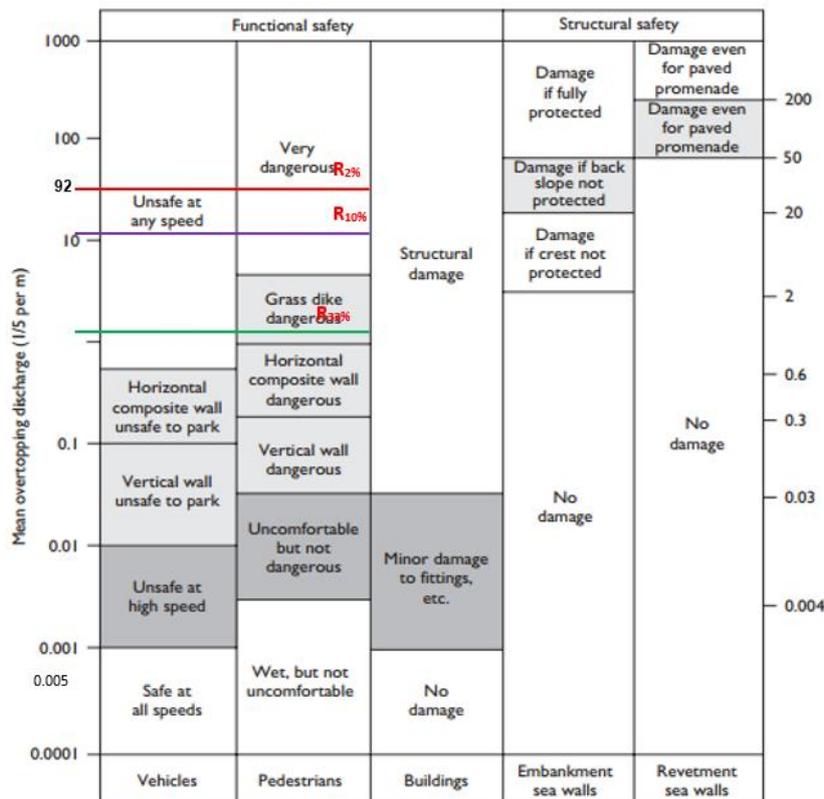Table 3. Overtopping discharge under HWL condition (l/s/m)

Figure 8. Overtopping discharge classification

4. Discussion

4.1 Influence of Wave Transformation on Run-up

The orthogonal pattern in Figure 5 shows that wave convergence occurred near the seawall, resulting in local amplification of wave height, particularly under the H2% condition. This phenomenon confirms that wave refraction and energy focusing significantly contribute to increased run-up magnitudes in front of coastal structures, consistent with waves propagating toward the shoreline [1][13]. When bathymetry promotes convergence of orthogonal, the localized energy concentration intensifies the run-up response on vertical structures.

4.2 Run-up Characteristics and Structural Effectiveness

The results indicate that the run-up ratio (R/H ≈ 3.0) for smooth surfaces closely matches the Van der Meer (1992) empirical formula, validating the use of probabilistic wave heights (H'2%, H'10%, and H'33%) for run-up estimation. However, the magnitude of run-up—up to three

times higher than the incident wave height—suggests that the current seawall geometry (vertical, smooth surface) amplifies rather than dissipates wave energy.

At MSL, $R_{2\%}$ exceeded the crest by 1.7 m, indicating that overtopping can still occur even under average water level. Under HWL, all R values surpassed the crest height, confirming that overtopping is inevitable during high tides combined with extreme waves. This finding demonstrates that the current seawall configuration is ineffective in reducing run-up and fails to meet safety requirements for probabilistic extreme conditions.

The calculated run-up ratios obtained in this study (R/H ≈ 3.0) are consistent with the empirical correlations reported for smooth seawalls, confirming the validity of using $H_{2\%}$ as the basis for estimating $R_{2\%}$. The agreement between analytical results, empirical formulations, and field observations further supports the robustness of the adopted probabilistic approach.

4.3 Overtopping Risk Classification and Field Validation

The computed overtopping discharges under MSL (0.1–8.8 l/s/m) and HWL (5-92 l/s/m) based on Overtopping functional safety classification. Under HWL conditions, exceeds the threshold for structural damage, indicating a high risk of severe functional impact on surrounding port and terminal facilities. It is important to note that classification primarily refers to functional safety, reflecting the extent of potential disturbance or damage to facilities behind the seawall, rather than failure of the structure itself. Field documentation from 2020 confirmed that overtopping events caused significant disruption and damage to nearby port facilities, while the concrete seawall remains physically intact.

From a structural safety perspective, the existing seawall can therefore be categorized as no damage, as the structure retained its integrity and stability despite repeated overtopping. However, under extreme run-up conditions ($R_{2\%}$), even paved promenades or adjacent facilities are predicted to not do damage, consistent with overtopping discharge classification. Thus, the seawall is effective in preventing structural damage to itself, but overtopping can still cause functional damage to the facilities and infrastructure located behind it.

The consistency between the theoretical and empirical predictions and observed conditions validates that the analytical framework combining Iribarren-based run-up estimation with overtopping formulation provides an accurate and field-representative assessment of overtopping risk at the Serui Fuel Terminal.

4.4 Implication for Seawall Design

The results reinforce that vertical concrete seawalls with smooth surfaces are inherently vulnerable to overtopping, especially as the Iribarren number increases [5]. This is consistent with other studies [6][7] that recommend alternative configurations such as stepped revetments, recurved parapets, or dual-protection systems to enhance wave energy dissipation and reduce overtopping volumes. For future design considerations at the Serui Fuel Terminal, incorporating such adaptive structural modifications could significantly improve coastal resilience under combined probabilistic wave and tidal conditions.

5. Conclusions

Based on the analysis of wave run-up and overtopping discharge under the combined effects of probabilistic wave conditions and tidal levels (MSL and HWL), it is concluded that the existing seawall at the Serui Fuel Terminal is unable to effectively prevent overtopping, particularly during high tides under $H'_{2\%}$ wave conditions. The maximum run-up reached 3.3 m, significantly exceeding the crest elevation of +1.93 m (MSL), resulting in an overtopping discharge of 92 l/s/m, classified as high functional damage risk based on functional safety criteria. The seawall itself remained structurally intact, but overtopping caused functional damage to port and terminal facilities located behind it. Even under MSL conditions, extreme waves occurred, indicating that the current structure is unsafe even under both normal and high-water conditions. These

findings are consistent with field observations (2020) and validated theoretical predictions. confirming that vertical and smooth-surfaced seawalls are less effective in dissipating wave energy, especially at higher Iribarren numbers. Therefore, it is recommended to redesign the structure using adaptive approaches such as increasing crest elevation, applying stepped or porous configurations, or implementing dual-protection systems to mitigate overtopping risks under extreme probabilistic conditions. This study provides a validated methodological framework for integrating probabilistic wave analysis into seawall design, offering a practical reference for improving coastal resilience in critical infrastructure areas such as the Serui Fuel Terminal.

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