

Article

Characterization of Overtopping Volumes from Focused Wave Groups over Smooth Dikes with an Emerged Toe: Insights from Physical Model Tests

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Abstract: This research examines the overtopping volumes associated with focused wave groups on smooth dikes with an emerged toe. Focused wave groups are employed to represent the highest waves of random sea states in a compact form, obviating the need to model the entire irregular wave train. This study investigates how overtopping volumes are affected by focus location and phase. A total of 418 experimental tests were gathered and analyzed. Data with overtopping volumes below 600 L per meter (prototype conditions) were excluded in order to focus on extreme overtopping events, resulting in 324 relevant test cases. The experiments used first-order wave generation theory to analyze structural response. Subsequent studies will address the errors induced by this approximation and compare it with second-order wave generation. The experiments simulated extreme wave impacts on an idealized coastal layout, comprising a 1:6.3 foreshore slope and three different dike slopes, including vertical structures, with the initial still water level set below the dike toe. This study employed the NewWave theory to generate focused wave groups, with the objective of extending recent research on wave overtopping under varied conditions. The results, analyzed in both dimensional and non-dimensional forms, indicate that overtopping volumes are significantly influenced by the focus phase. Critical focus locations were identified at a distance of one-third of the deep-water wavelength from the toe.



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Keywords: wave overtopping volumes; focused wave groups; experimental modeling; emerged toe; sea dike; extreme events

1. Introduction

Wave overtopping is considered a key aspect of coastal structural design. The main challenge in assessing the resilience of urban areas to wave overtopping and associated flooding is the accurate estimation of overtopping: this includes not only the determination of mean discharge values, but also the assessment of the volumes associated with individual overtopping events caused by large waves within a sea state. All of this is exacerbated by the changing climate [1]; climate change scenarios, in fact, including sea level rises and increases in storminess, raise the critical question of how to protect coastal urban areas from flood risks and sea level rises. Recent events such as Storms Gloria in January 2020 [2] and Ciarán in early November 2023 have highlighted the vulnerability of coastal urban areas. This increased risk implies significant changes in coastal conditions, with an expected increase in average water levels and wave variables such as wave height and period, having important implications for wave-driven coastal processes, according to the study by Morim et al. [3].

The design of coastal structures to minimize or prevent wave overtopping is more and more necessary to ensure coastal safety. Traditionally, the mean flow rate has been used as a design criterion, but there is still uncertainty as to whether it adequately represents the real hazard. The EurOtop manual [4] establishes criteria based on the average discharges, while

recognizing the difficulties of establishing precise limits for all conditions. Studies, such as those by Endoh and Takahashi [5] and Sandoval and Bruce [5], highlight the limitations of a single average flow value or maximum overtopping volume. Recently, there has been a shift towards re-evaluating the risks associated with wave overtopping. Instead of relying on average flows, a new set of criteria will be established based on the specific characteristics of each overtopping flow [6]. This is supported by various studies [5,7–10]. Improving the understanding of individual overtopping flows is crucial to guiding the design of coastal structures. This has been emphasized in [7–9]. It is crucial to assess the distinct risks associated with distinct overtopping events, such as the potential to sweep pedestrians off their feet, or to require proper evacuation measures. Accurately predicting and characterizing significant overtopping events is crucial in certain scenarios. As highlighted by Hughes and Thornton [7] and Whittaker et al. [10], the accurate structural design of coastal defenses must consider individual wave properties.

In order to characterize individual overtopping volumes on sea dikes with an emerged toe and associated with maximum wave heights in a random sea state, the present study employed focused wave groups rather than simulating whole irregular sea states. The generation of focused wave groups offers several advantages, including improved repeatability, the ability to evaluate model and scale effects, the potential for improved measurement, and enhanced model resolution for large wave interactions [10].

In the field of offshore engineering, the so-called NewWave theory was introduced in [11] as a compact and focused wave group specifically designed for engineering purposes. NewWave provides an alternative approach to studying wave–structure interaction (WSI) during extreme events. It models the most statistically probable surface elevation shape associated with the largest waves. These waves are characterized by a specified exceedance probability within a random sea state [12]. More and more applications in the field of coastal engineering have used NewWave and focused wave groups. In fact, focused wave groups can help understand the connection between wave properties and structural responses, either centered on coastal defenses (e.g., [13–15]) or applied to floating structures and wave energy converters (e.g., [16–18]).

Whittaker et al. [19] validated the use of focused wave groups for WSI problems in a coastal zone, suggesting that a single incident wave group could replicate extreme coastal responses within a specific sea state. In [10], the authors studied the impact of focused wave groups on an inclined seawall, analyzing overtopping volumes and horizontal forces through physical laboratory experiments and numerical simulations. The research found that total overtopping volumes strongly depend on focus location, phase angle at focus, and linear wave amplitude. Changing the phase of the group at focus could significantly increase the total overtopped volume.

Craciunescu and Christou [20] developed a model for wave breaking energy dissipation using focused wave groups. Xiao et al. [21] conducted an experimental and numerical investigation of focused wave groups across a typical fringing reef profile, examining their impact on a vertical wall attached to the reef flat. They suggested that extreme coastal responses within a specific sea state can be replicated using only a single incident wave group. Recently, Mortimer et al. [22] explored run-up on vertical walls in shallow and intermediate water, focusing on the effects of second-order correction for generating focused wave groups. Additionally, Altomare et al. [23] employed focused wave groups to investigate the structural response and failure mechanism of a pier under severe wave breaking conditions.

The present article employs similar methodology as in [10] but extends the analysis further to different hydrodynamic conditions, foreshores, and dike slopes. While in [10], the authors used NewWave to analyze the overtopping of gentle dikes with a 1:2 slope on a 1:20 planar beach and submerged toes, in this study, we examined a varying foreshore slope with dikes that had an emerged toe (i.e., still water level below the toe level) and different slopes, namely 1:2, 1:0.5, and vertical. The influence of water level was examined, whereas in [10], only one water level was studied. The importance of the water level lies

in the induced wave breaking and its location. Differences in wave overtopping results for different water levels are caused by this breaking, which eventually affects energy dissipation and structural responses. Focused wave groups were generated by means of first-order wave generation theory for the present work. A first analysis based on first-order approximation is acceptable at a preliminary stage, although this limits the applicability of the present study and requires future analysis implementing second-order wave generation theory [24,25]. In fact, linear or first-order theory might induce the generation of spurious free waves, especially in extremely shallow water conditions. The limitations of the results will be discussed further in the next sections.

This document is organized into separate sections, each dedicated to different facets of this study. Section 2 elucidates the experimental setup. Section 3 establishes the scaling of the overtopping volume and defines the parametric space for volume dependence. Section 4 presents the experimental results, detailing the reliance of both dimensional and non-dimensional overtopping volumes on focused wave parameters, geometrical configurations, and hydrodynamic conditions. Section 5 engages in a discussion of the research findings and, lastly, Section 6 derives conclusions from the investigation.

2. Experimental MODEL

2.1. Model Setup

The experimental investigation of this study was carried out in the CIEMito small-scale wave and current flume at the Maritime Engineering Laboratory of Universitat Politècnica de Catalunya—BarcelonaTech (LIM/UPC). This flume setup is depicted in Figure 1. The model's scale was 1:50, based on Froude similarity.

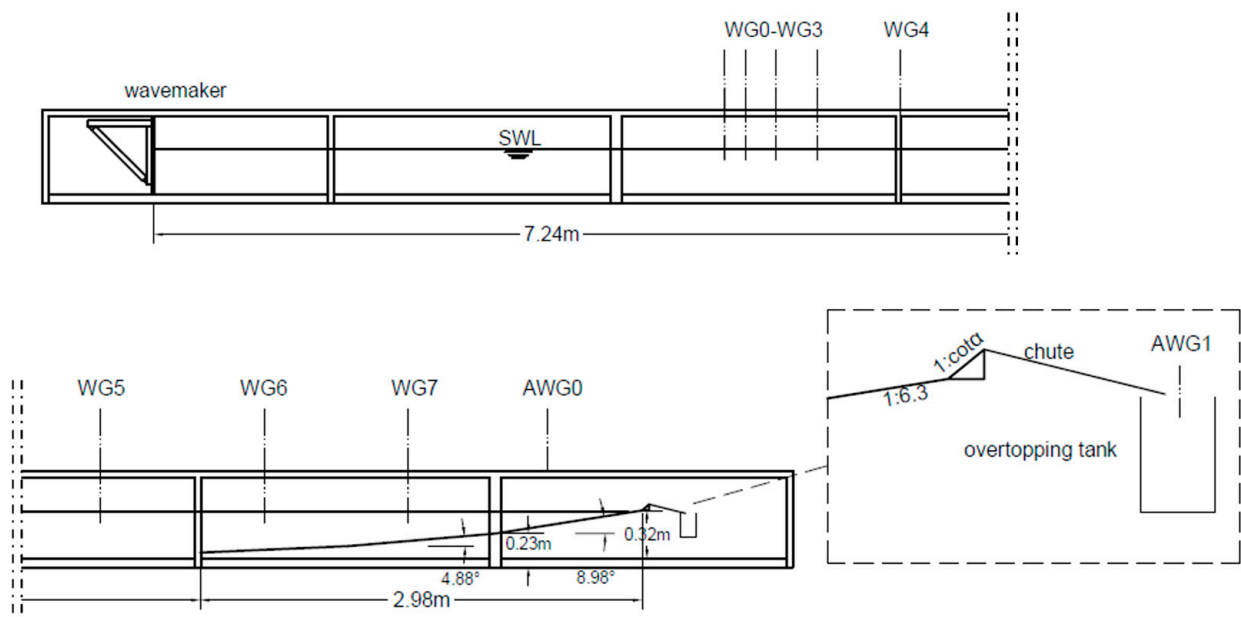


Figure 1. Experimental model setup in the CIEMito flume, with details of the dike, where $\cot\alpha = [0, 0.5, 2]$, and the overtopping tank.

The model, constructed from plywood, features a dike at the end of a sloping emerged foreshore designed to induce wave breaking before reaching the toe of the structure. Various dike slopes with the same structural height were examined, including a vertical wall and two sloping dikes (specifically 1:2 and 1:0.5, being H:V). The foreshore consisted of three modular plywood elements, each measuring 1 m in length. The last element, including the emerged part of the beach, had a slope of 1:6.3, which was employed to induce plunging wave breaking for the selected wave conditions, while the slope of the stretch before it had a slope of 1:11. For each dike slope, the structural height was maintained equal to 0.04 m.

Positioned at a distance of 10.22 m from the wavemaker at its resting position, the dike toe was situated at $z = 0.32$ m, where $z = 0$ m represents the vertical coordinate of the flume bottom at the wavemaker location.

Resistive wave gauges (WG) and one acoustic wave gauge (AWG0) distributed along the flume were employed to measure water surface elevation, and an overtopping tank, equipped with an ultrasonic proximity sensor (AWG1), was utilized to quantify the volume of overtopping. The specific locations of the wave gauges are indicated in Table 1.

Table 1. Wave gauge location for surface elevation measurement along the CIEMito flume.

Wave Gauge	WG0	WG1	WG2	WG3	WG4	WG5 *	WG6 *	WG7 *	AWG0 *
Distance from the wavemaker (m)	4.00	4.15	4.36	4.65	5.23	6.56	7.67	8.64	9.58

* Wave gauges where focal location was established.

Scale effects were assessed on wave overtopping volumes at the employed 1:50 model scale. It is worth mentioning that Heller [26] outlined criteria for flow–structure interaction, suggesting investigation scales that balanced model size and scale effects. Moreover, large-scale tests for vertical structures, as indicated in [4], validated the scalability of formulas derived from small-scale studies [27]. Notwithstanding this, further examination is needed to fully exclude scale effects. The analysis concentrated on viscous forces and surface tension, aligning with [4]. Reynolds and Weber numbers for wave overtopping (Re_q and We_q) were computed and compared to critical limits ($Re_q > 10^3$ and $We_q > 10$), as defined in [28]. The calculation of Re_q and We_q involves assessing the run-up of focused wave groups, overtopping flow velocity, and depth. To perform the calculation of Re_q , wave run-up estimation, detailed in [29], was utilized. Deep-water wave characteristics were used for the scope, i.e., measured at the WG0 location. For We_q , the overtopping flow velocity and depth were determined from the procedure in [4]. The calculated Re_q and We_q for the cases presented in this study surpassed 10^3 and 10, respectively, indicating the absence of scale effects.

2.2. Hydrodynamic Conditions: Focused Wave Groups

The time series for each wave group was generated using the NewWave theory. NewWave was originally designed for the generation and propagation of a compact wave train on a horizontal bottom. The selected focal point regulates the dispersion of the wave group during shoaling and breaking while propagating. A NewWave-type focused wave group comprising N infinitesimal wave components is given by the following equation:

$$\eta(x, t) = \frac{A}{\sigma^2} \sum_{i=1}^N S_{\eta\eta}(\omega_i) \cos\left(k_i(x - x_f) - \omega_i(t - t_f) + \phi\right) \Delta\omega \quad (1)$$

where $S_{\eta\eta}$ is the power spectral density, t is the time, x is the horizontal distance from generation, ϕ is the phase at focus, ω is the angular frequency, σ is the standard deviation of the sea state (being $\sigma^2 = \sum S_{\eta\eta}(\omega_i) \Delta\omega$), and k_i is the wavenumber of the i -th wave component with angular frequency ω_i and related to it by the familiar linear dispersion relation $\omega^2 = gk \times \tanh(kh)$, where g is the acceleration due to gravity and h is the water depth [10]. All wave components come into phase at the focus location x_f and focus time t_f to form a large wave with a linear focus amplitude equal to A , calculated to represent “the amplitude of the largest wave in a sea surface time series of N waves in a narrow-banded linear random sea” [24]. If a Rayleigh distribution of the wave height is assumed, then A can be defined as the following:

$$A = \sqrt{(2\sigma^2 \ln N)} \quad (2)$$

Once the target significant wave height, H_{m0} , was defined, being $H_{m0} = 4\sigma$, the target value of A was calculated from the standard deviation, σ . Table 2 lists the range of

parameters examined in the present study. Wave conditions are expressed in model scale. Values of a significant wave height and spectral period reported in the table correspond to the ones measured at the WG0 location, rather than the target or theoretical ones. This choice was justified by the fact that overtopping volumes would be scaled by the measured deep-water wave height and wavelength (see Section 3), which were employed in lieu of local wave conditions at the toe of the structure. This was due to the difficulty in accurately estimating the wave conditions at the toe in the event of wave breaking and very or extremely shallow water conditions. Further application, in fact, would necessitate sophisticated numerical modeling and/or ad hoc experimental campaigns [30].

Table 2. Test conditions and numbers of data for the overtopping physical model tests for each dike slope.

Parameter	Dike 1:2	Dike 1:0.5	Vertical Dike
H_{m0} (m)	0.0456–0.0712	0.0498–0.0760	0.0468–0.0726
$T_{m-1,0}$ (s)	1.32–1.82	1.48–1.82	1.42–1.82
x_f (m) (relative to the wavemaker)		6.56, 7.66, 8.64, 9.58	
$x_{f,t}$ (m) (relative to the dike toe)		0.64, 1.58, 2.55, 3.66	
φ (°)		0, 90, 180, 270	
h (m) (at the wavemaker)	0.28, 0.29, 0.30, 0.31	0.28, 0.30, 0.31	0.28, 0.29, 0.30, 0.31
No. data	155	70	99

All data with an overtopping volume lower than 600 L/m (value expressed under prototype conditions) were excluded from the analysis, concentrating on extreme wave conditions and overtopping events only. It is worthy to remember that 600 L/m is the threshold of tolerable overtopping for pedestrians indicated in [4]: hence, following the analysis of 418 tests, 324 relevant test cases were identified for further investigation in the present study. With regard to the prototype dimensions, the wave conditions corresponding to the aforementioned data exhibited a deep-water significant wave height that ranged between 2.28 m and 3.8 m, with a spectral period between 9.33 s and 12.91 s. The crest freeboard varied between 2.55 m and 4.2 m.

Whittaker et al. [19] confirmed the continued applicability of the NewWave theory in relatively shallow waters ($kh < 0.5$), indicating that linear frequency dispersion remains the primary mechanism despite the increasing influence of nonlinear effects due to changes in bathymetry. It is important to highlight that the minimum value of kh at the focus location for the tests conducted in the current study was 0.10. This value was calculated considering the local water depth of the nearest point to the dike and the wavelength in deep waters. This location corresponded to extremely shallow foreshore conditions, as per the classification proposed in [31], with a ratio of local water depth to deep-water significant wave height, $h_t/H_{m0,o}$, equal to 0.78. In most cases, waves broke before reaching this location. Consequently, all assumptions based on the propagation of a compact wave train and linear theory became invalid. Despite this, it was considered worthwhile to investigate the response when focusing was theoretically induced after the waves had broken.

3. Parameter Definition and Scaling Laws in Wave Overtopping

The problem under study is defined by eight variables. The first one and final object of this study is the overtopping volume associated with the maximum wave height in a random sea state, here computed as the total volume caused by the focused wave group. Two other variables are the focus wave location (x_f or $x_{f,t}$) and the phase at focus (ϕ). The remaining five variables are related to the hydrodynamic conditions and the geometrical layout. These variables include the deep-water significant wave height ($H_{m0,o}$), deep-water spectral period ($T_{m-1,0,o}$), water depth (either in deep waters, h , or at the toe, h_t), dike slope ($\cot\alpha$), and foreshore slope ($\cot\theta$). In order to facilitate comparisons of results across a range of wave conditions and dike slopes, and given the considerable variability in hydrodynamic deep-water conditions, dimensionless variables were employed instead of dimensional

ones. At first, the total overtopping volume per meter width associated with the focused wave group, V_{max} , was scaled on the instantaneous volume flux over the half wave period, defined by [32], as

$$V_0 = \frac{H_{m0,o} L_{m-1,0,o}}{2\pi} \quad (3)$$

where $L_{m-1,0,o}$ denotes the deep-water wavelength calculated from the spectral period $T_{m-1,0}$. The method for achieving a dimensionless overtopping volume (V_{max}/V_0) was described and analyzed by Ibrahim and Baldock [33], hereafter referred to as IB2020. This method was also used in [34] for predicting mean overtopping discharge on promenades and further developed in [35] for overtopping on fringing reefs. In a physical sense, rationalizing the scaling of the volume flux involves equating it to the volume of fluid displaced by a wavemaker that finally reaches and overtops a structure, which presents a deficit in the freeboard with respect to the expected wave run-up. The volume flux V_0 will be used later on to compare the dependence of the overtopping volume for each dike slope and each initial water depth.

IB2020 finally proposed an empirical model for overtopping on truncated beaches. The volume of the overtopping is dependent on the offshore wave conditions and the foreshore slope angle. The proposed scaling factor is defined as

$$V^* = const^* V_0 \tan^n \theta f\left(\frac{R_c}{R_u}\right) \quad (4)$$

where n is either 0.5 or 1, R_c is the crest freeboard, and R_u the run-up height. It is important to note that the slope angle of the foreshore remained constant throughout our analysis. However, as will be explained subsequently, we considered the combined effect of the foreshore and dike slopes, by defining an equivalent foreshore slope. The equivalent slope will be employed for the definition of V^* based on Equation (4).

To consider the different dike slopes combined with the foreshore slope (where the waves were actually breaking before reaching the dike), the equivalent slope is proposed for the definition of the breaker parameter. The definition of the equivalent slopes resembles the one proposed in [36] but with an important difference. Wave run-up must be assessed as indicated in [36], employing the wave characteristics at the dike toe. However, this calculation was not performed to finally define the equivalent slope, because of the large uncertainty in applying the proposed semi-empirical formula for the wave run-up estimation for the studied layout (for instance, a dike with an emerged toe, from a gentle to vertical and steep foreshore). Hence, rather than employing an iterative approach to estimating the equivalent slope, the first estimate based on the crest freeboard and the deep-water significant wave height was used as the following:

$$\cot \delta = \frac{(R_c + h_t) \cot \alpha + (H_{m0,o} - h_t) \cot \theta}{(H_{m0,o} + R_c)} \quad (5)$$

For scaling the volume, combining Equations (4) and (5), we used the following:

$$V^* = V_0 \tan \delta \quad (6)$$

Furthermore, in order to study the variability in overtopping volumes in a non-dimensional form, three other dimensionless variables are defined. The first two of them are characteristic variables describing the wave overtopping based on deep-water wave conditions and local water depth [30]: the non-dimensional freeboard, $R_c/H_{m0,o}$ and the shallowness (see [31]), $h_t/H_{m0,o}$. The ratio between the water depth and wave height was previously employed in [37], but the local significant wave height at the toe of the structure was employed. Finally, a non-dimensional focused location, X , is defined as

$$X = \frac{x_t - x_f}{L_{m-1,0,o}} \quad (7)$$

where x_t is the location of the dike toe and $x_t - x_f = x_{f,t}$ expresses the distance between the dike and focus location, which is then scaled by the deep-water wavelength. Either the V_0 or V^* were employed as scaling factors for wave overtopping (i.e., factors employed to define a non-dimensional individual overtopping volume), not necessarily explicitly considering the influence of the water depth. By employing V_0 , this aspect was not considered, while using V^* , the local water depth was considered only to calculate the equivalent slope. Hence, we refer to the overtopping formula proposed in [30] for the average overtopping discharge. The formula is represented by Equations (8)–(15) and was expanded further in Equations (16) and (17) to obtain the scaling factor for the overtopping volume defined as $V' = qT_{m-1,0,o}$. This is actually consistent with the scale parameter of the Weibull distribution, which is usually employed to analyze individual overtopping volumes associated with a specific exceedance probability in a random sea state (see, for example, [4,38,39]). In fact, the individual overtopping volume is scaled by the mean value of the Weibull distribution, which can be expressed as the product of the mean discharge by the mean wave period, divided by the probability of overtopping waves in a whole random sea storm. Therefore, referring to [30], for vertical dikes with $h_t/H_{m0,o} \leq 0.1$, the mean overtopping discharge, q , can be expressed as the following:

$$\frac{q}{\sqrt{g \cdot H_{m0,o}^3}} = a \cdot \exp \left(-b \cdot \frac{R_c}{H_{m0,o}} + c \cdot \frac{h_t}{H_{m0,o}} \right) \quad (8)$$

where

$$a = 0.09 \cdot \frac{(\tan \theta)^{1.75}}{s_{m-1,0,o}^{0.90}}; \quad (9)$$

$$b = 6.05 \cdot \frac{s_{m-1,0,o}^{0.35}}{(\tan \theta)^{0.50}}; \quad (10)$$

and

$$c = 1.45 \cdot \frac{s_{m-1,0,o}^{3.25}}{(\tan \theta)^{3.45}}. \quad (11)$$

Meanwhile, for sloping dikes with $h_t/H_{m0,o} \leq 0.1$, the formula is

$$\frac{q}{\sqrt{g \cdot H_{m0,o}^3}} = d \cdot \exp \left(-e \cdot \frac{R_c}{H_{m0,o}} + f \cdot \frac{h_t}{H_{m0,o}} \right) \quad (12)$$

where

$$d = 1.35 \cdot (\tan \theta)^{0.35} \cdot s_{m-1,0,o}^{0.85} \quad (13)$$

$$e = 3.75 \cdot \frac{s_{m-1,0,o}^{0.70}}{(\tan \theta)^{0.70} \cdot (\tan \alpha)^{0.60}} \quad (14)$$

and

$$f = 0.35 \cdot \frac{s_{m-1,0,o}^{0.35}}{(\tan \theta)^{1.30}} \quad (15)$$

The coefficients a , b , c , d , e , and f are therefore function of the seabed slope, the dike slope, and the deep-water wave steepness, defined as $s_{m-1,0,o} = H_{m0,o}/L_{m-1,0,o}$. The scaling volume based on [30], hereafter indicated as V_{L21} , can be expressed for vertical structures as

$$V_{L21} = T_{m-1,0,o} \sqrt{g \cdot H_{m0,o}^3} a \cdot \exp \left(-b \cdot \frac{R_c}{H_{m0,o}} + c \cdot \frac{h_t}{H_{m0,o}} \right) \quad (16)$$

Meanwhile, for sloping dikes, it can be expressed as

$$V_{L21} = T_{m-1,0,0} \sqrt{g \cdot H_{m0,0}^3} d \cdot \exp \left(-e \cdot \frac{R_c}{H_{m0,0}} + f \cdot \frac{h_t}{H_{m0,0}} \right) \quad (17)$$

4. Results

The results of the experimental campaign are presented in both dimensional and dimensionless forms in the following sections. For the former, although all quantities were previously defined in model scale, it was more practical and immediately understandable to express the measured overtopping volumes in an upscaled format to prototype conditions.

4.1. Wave Transformation and Overtopping Volume Characteristics

Figure 2 shows the free-surface elevation at each wave gauge position of a focused wave group producing a total volume over the 1:2 dike which resulted in being larger than 2000 L/m (this value is expressed in the prototype).

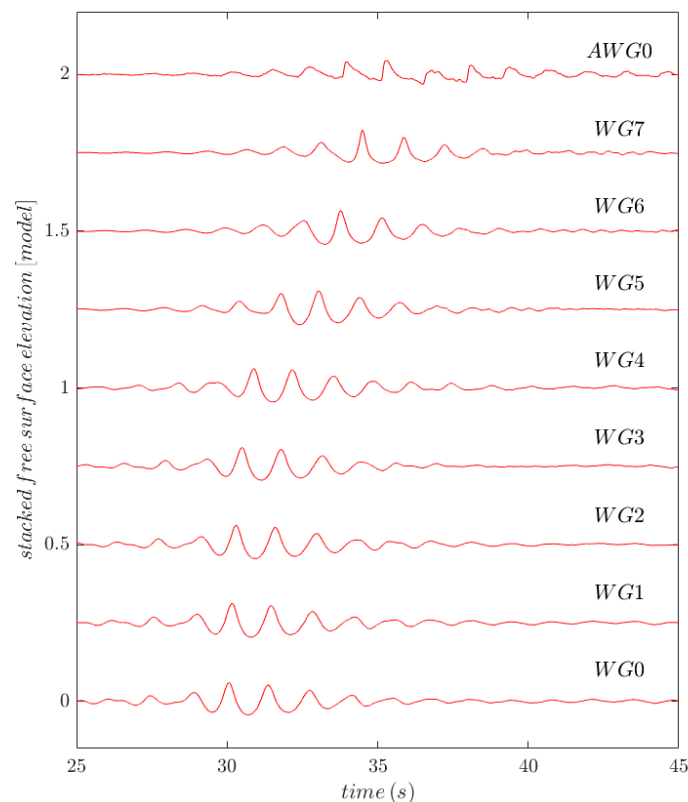


Figure 2. Example of free-surface elevations (in meters) at nine wave gauges (results in model scale).

The focus phase is equal to 0° (crest-focused) in the shown example and focus location is at the WG7 position ($x_f = 7.67$ m). Wave transformation is clear between WG7 and AWG0 ($x = 9.58$ m), where wave shoaling and breaking took place. Snapshots of the focused wave group overtopping the three sea dikes are reported in Figure 3 for the same test case and water depth, namely $h = 0.30$ m, $H_{m0,0} \approx 0.065$ m, and $T_{m-1,0,0} \approx 1.75$ s, $\phi = 270^\circ$, $x_f = 9.58$ m (AWG0 location). The process became more violent and turbulent as the dike slope increased. Meanwhile, for the 1:2 dike (Figure 3a), the wave overtopped the slope smoothly (almost no splashes), typical of the so-called “green” overtopping flows, for the 1:0.5 (Figure 3b) and vertical slopes (Figure 3c); this process became more and more turbulent, due to the higher exerted wave reflection and the consequent inversion of the wave momentum flux.

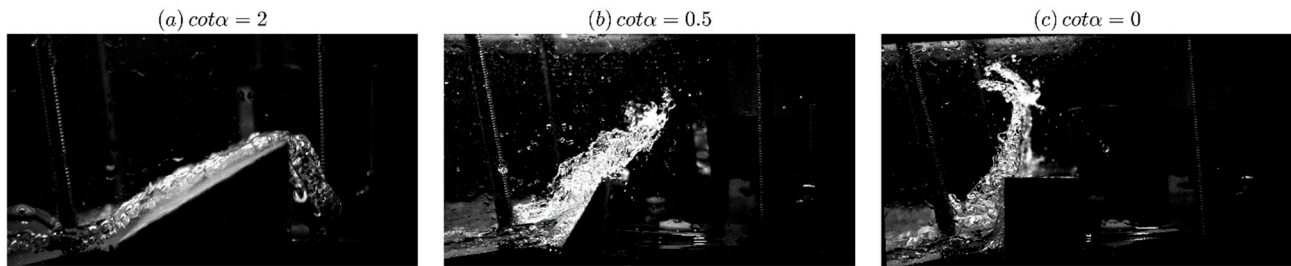


Figure 3. Snapshots of wave overtopping of the three different dike slopes: examples of large individual overtopping.

4.2. Focused Wave Parameter Space

4.2.1. Dimensional Variables

Variation in the overtopping volume based on focused wave location and phase was assessed for each dike slope and initial water level. The investigation included four different water levels for the 1:2 and vertical slopes, namely 0.31 m, 0.30 m, 0.29 m, and 0.28 m. For the 1:0.5 slope, only three water levels were tested, namely 0.31 m, 0.30 m, and 0.28 m. It is important to note that the toe was located at $z = 0.32$ m, resulting in an emergent toe for all water levels.

The parameter space investigated with focused wave groups was already described and reported in Table 2. The coordinates of x_f are expressed with respect to the position of the wavemaker at rest ($x = 0$ m). It is important to note that the toe of the dike was located at $x = 10.22$ m. All aforementioned dimensional quantities are expressed in model scale. Four focused locations and four different phase angles with increments of 90° were considered. The focal points were chosen to vary from the horizontal bottom, 0.68 m from the beach toe to 0.64 m from the toe of the dike, covering a length of approximately 3 m along the wave flume, corresponding to each focal position to the wave gauges WG5, WG6, WG7, and AWG0, respectively.

The variation in total volumes as a function of the focus phase and location for different dike slopes and water depths are shown in Figures 4–6. The volumes were scaled up to prototype conditions. In order to facilitate visualization of the results, the volumes are expressed in logarithmic scale. It should be noted that the color bars have different scales for each dike slope. Using the same scale for all dike slopes would prevent the appreciation of the small variations in volume especially for the cases of low water depths. Experimental contours were smoothed by interpolating the results onto a finer grid ($\Delta x_f = 0.15$ m, $\Delta \phi = 15^\circ$). The blank areas in the figures indicate where test cases corresponding to volumes smaller than 600 L/m were removed.

Overall, the results indicate that varying the locations and phases of focused waves can optimize the total volume for different water levels. Despite the different experimental setups, the bands of maximum and minimum volumes looked similar to those presented in [10,15], where the wave run-up and overtopping of a focused wave group was studied for mild foreshore slopes and 1:2 dikes. The maximum overtopping volumes were observed to follow a diagonal pattern, with the phase leading to large volumes decreasing as the focus location moved closer to the dike toe.

While there were some discernible patterns, the outcomes for the 1:0.5 slope and the vertical dike were more scattered. In fact, the laboratory measurements of the total overtopping volume presented two difficulties for correct interpretation. First, as shown, they were quite sparse in x_f , which created some issues when using a standard contour plot (see also [15] to this respect). Secondly, the number of data points for specific combination of dike slope and water depth values was relatively limited to the following: 5 data for $\cot \alpha = 0$ and $h = 0.28$ m, 27 data for $\cot \alpha = 0$ and $h = 0.30$ m, 27 data for $\cot \alpha = 0.5$ and $h = 0.31$ m, 12 data for $\cot \alpha = 0.5$ and $h = 0.28$ m, and 12 data for $\cot \alpha = 2$ and $h = 0.28$ m. This fact reduced the accuracy of the analysis and the data interpolation. Finally, although gathered for different water depths, they included data from all different wave conditions, namely

the wave height and wave period. About the last, Xiao et al. [21] noticed the influence of the wave period on the wave-structure interaction induced by a focused wave group, a fact that was not explicitly addressed in other works. There was, therefore, a clear need to present the data in a uniform and scaled manner to enable proper comparison.

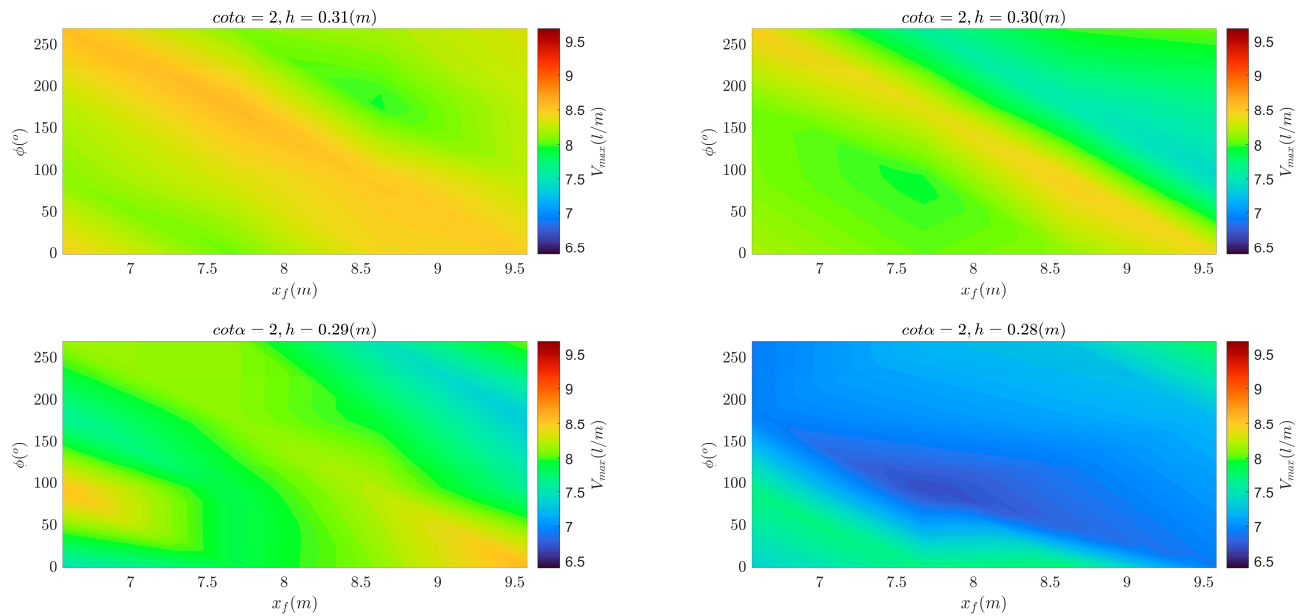


Figure 4. Variation in total overtopping volume (upscaled to prototype and expressed in logarithmic scale) over the range of focus locations, x_f , phases (at focus), and water levels tested for the 1:2 dike slope.

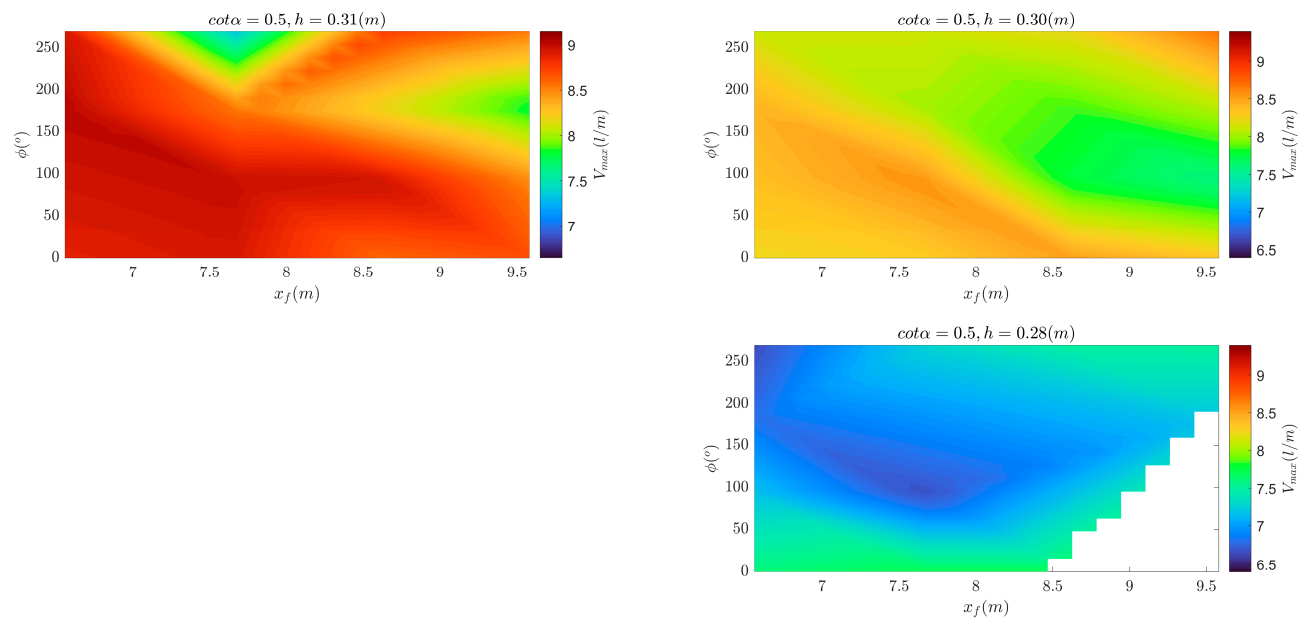


Figure 5. Variation in total overtopping volume (upscaled to prototype and expressed in logarithmic scale) over the range of focus locations, x_f , phases (at focus), and water levels tested for the 1:0.5 dike slope. Blank areas correspond to test cases excluded from the analysis (i.e., $V_{max} < 600$ L/m).

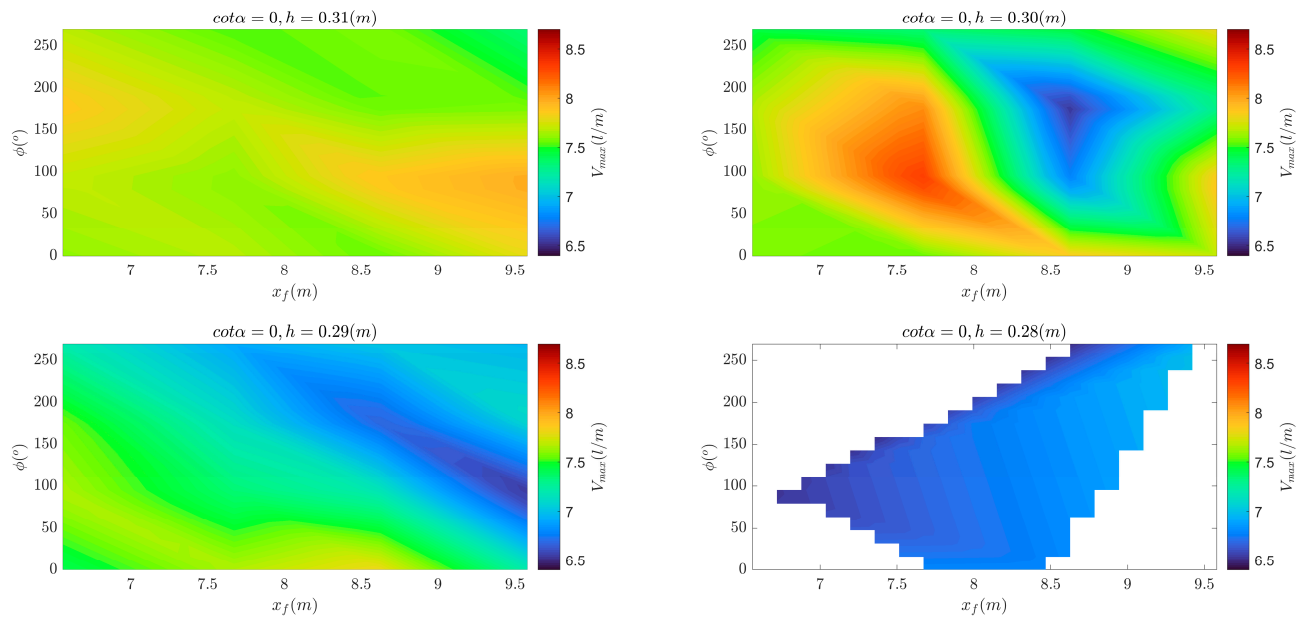


Figure 6. Variation in total overtopping volume (upscaled to prototype and expressed in logarithmic scale) over the range of focus locations, x_f , phases (at focus), and water levels tested for the vertical dike. Blank areas correspond to test cases excluded from the analysis (i.e., $V_{max} < 600$ L/m).

4.2.2. Dimensionless Variables

The volumes were scaled initially by the volume flux V_0 (see Equation (3)). The variations in dimensionless volumes as functions of the focus phase and location for different dike slopes and water depths are shown in Figures 7–9. Additionally, the position of the focused is expressed in dimensionless form (see Equation (7)) for a better understanding of the dependence of the phenomenon on the wave period.

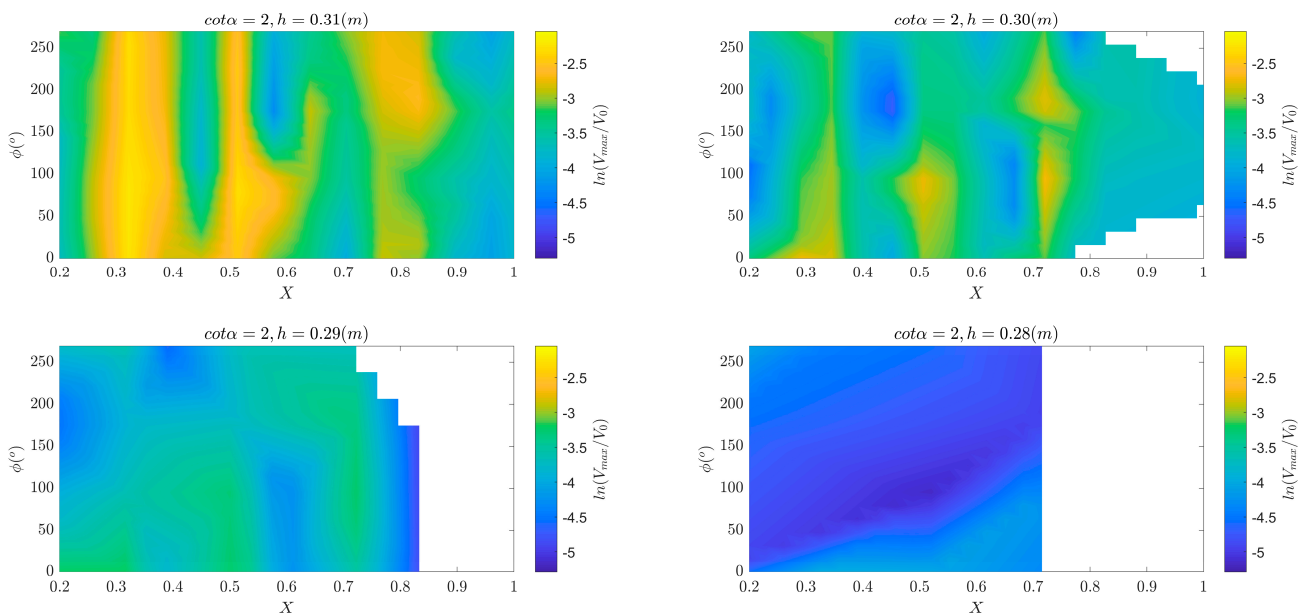


Figure 7. Variation in non-dimensional total overtopping volume (V_{max}/V_0) over the range of non-dimensional focus locations, X , phases (at focus), and water levels tested for the 1:2 dike slope.

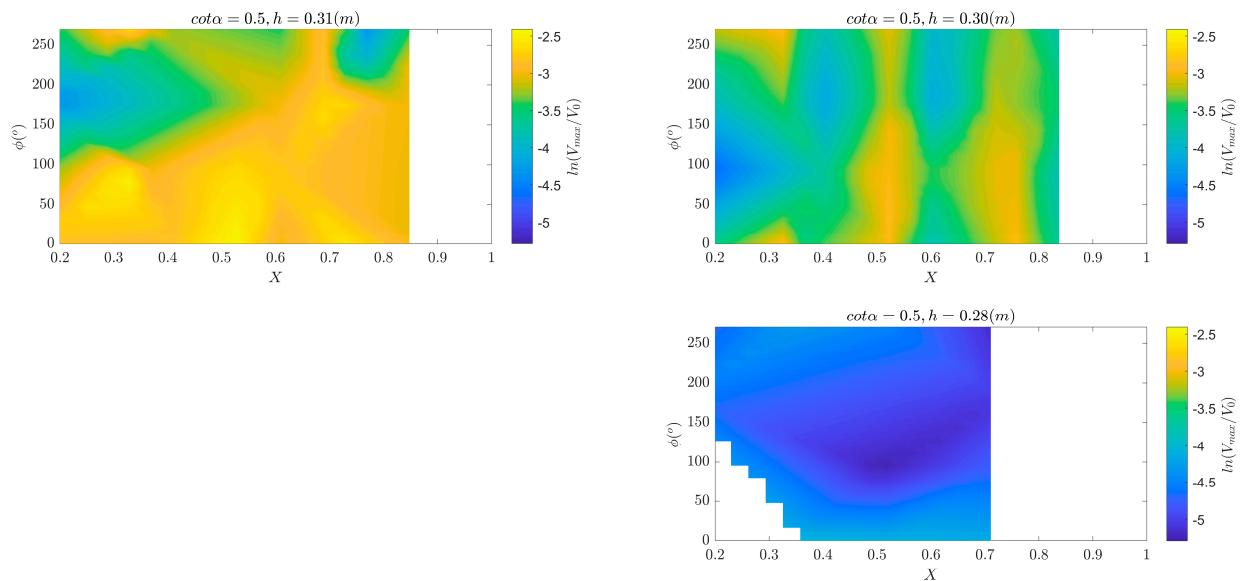


Figure 8. Variation in non-dimensional total overtopping volume (V_{max}/V_0) over the range of non-dimensional focus locations, X , phases (at focus), and water levels tested for the 2:1 dike slope.

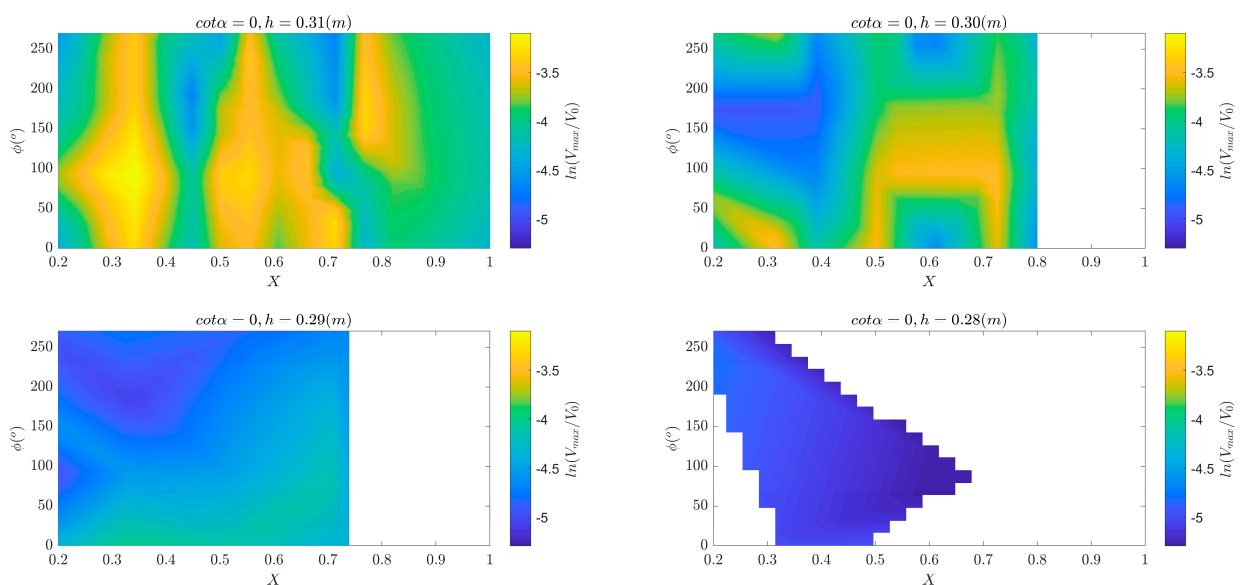


Figure 9. Variation in non-dimensional total overtopping volume (V_{max}/V_0) over the range of non-dimensional focus locations, X , phases (at focus), and water levels tested for the vertical dike.

In general, the overtopping volume decreased as the freeboard height increased and the toe became more exposed. Clear vertical bands, proportional to the wavelength, can be identified in the figures. For all structures, we can find a specific dimensionless focus location that maximizes the volume. For $\cot\alpha = 2$ and water levels 0.31 m and 0.30 m, at a distance from the dike toe equal to approximately 0.30 and 0.52 of the wavelengths, a peak in the measure volume was noticed. A third peak was noticed at about $0.75 L_{m-1,0,\rho}$, although less in magnitude. For an initial water depth of 0.28 m, there were very few overtopping cases, making it difficult to interpret the results. For $\cot\alpha = 0.5$ and $h = 0.30$ m, similar values of X as those previously mentioned indicated that the overtopping volumes were maximized. However, the interpretation of the results for $h = 0.31$ m and 0.28 m was challenging due to the limited data collected. The optimal relative distance for the vertical dike appeared to shift slightly offshore ($X = 0.34$ and 0.56) for $h = 0.31$ m. However, it was difficult to draw clear conclusions for the other three water depths at this stage. The 1:2

dike exhibited large volumes for phases of 0° and 90° , for $h = 0.31$ m and 0.29 m. A peak at $x_f = 0.75 L_{m-1,0,0}$ and $\phi = 270^\circ$ was also noticeable. In the case of the 1:0.5 dike slope, volumes seemed to maximize for asymmetric wave forms in the groups (i.e., phases of 90° and 270°). The vertical slope showed similar behavior for $h = 0.31$ m, while for $h = 0.29$ m a wider band between $X = 0.5$ and $X = 0.75$ was observed. For $h = 0.29$ m, instead, large volumes were observed for the crest-focused wave groups only (i.e., $\phi = 0^\circ$).

It is evident that when the overtopping volume was scaled by the volume flux and considering non-dimensional distances from the dike toe, similar patterns for the three different dike slopes were recognized, particularly for the two highest water levels. Whitaker et al. [10] observed that large overtopping volumes increased monotonically with focus wave amplitude, and clear bands dependent on focus location and phase could be identified. However, the authors attributed the different behavior of small overtopping volumes to wave–wave interaction within the focus group. If the first wave in the group is reflected instead of overtopping the structure, it may cause the second wave to break prematurely and lose most of its energy. This can happen more frequently and with larger waves on steep slopes, which reflect more and cause greater energy loss. The interaction between waves and steep structures, which here was dominated by heavy wave breaking, reflection, and changes in wave momentum, even resulting in high uprush and splashes, made it more challenging to generalize the results.

5. Discussion

5.1. Influence of the Wave Period on Overtopping Volumes

As noted in Section 4.2.1, Xiao et al. [21] highlighted the influence of a wave period on the interaction between waves and structures caused by a focused wave group, a topic that had not been specifically addressed in previous studies. Here, the variation in total volumes as a function of the wave period is shown for different dike slopes and different focused locations. The dependence of the volumes on the deep-water wave period and dimensionless freeboard is depicted in Figures 10 and 11. In the former, three plots are shown, one per each dike slope. In the latter, a distinction was made for each focus location. As before, in order to facilitate the visualization of the results, the volumes are expressed in logarithmic scale. Experimental contours were smoothed out by interpolating the results onto a finer grid ($\Delta T_{m-1,0} = 0.09$ s and $\Delta R = 0.18$, being $R = R_c/H_{m0,0}$).

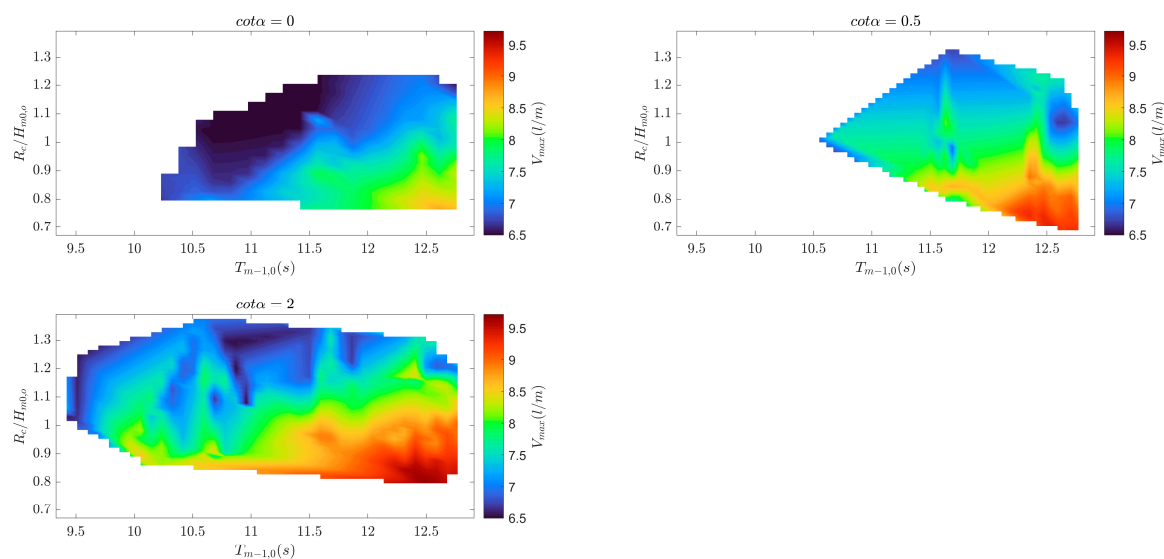


Figure 10. Variation in total overtopping volume (upscaled to a prototype and expressed in logarithmic scale) over the range of dimensionless freeboards and deep-water wave periods for each dike slopes.

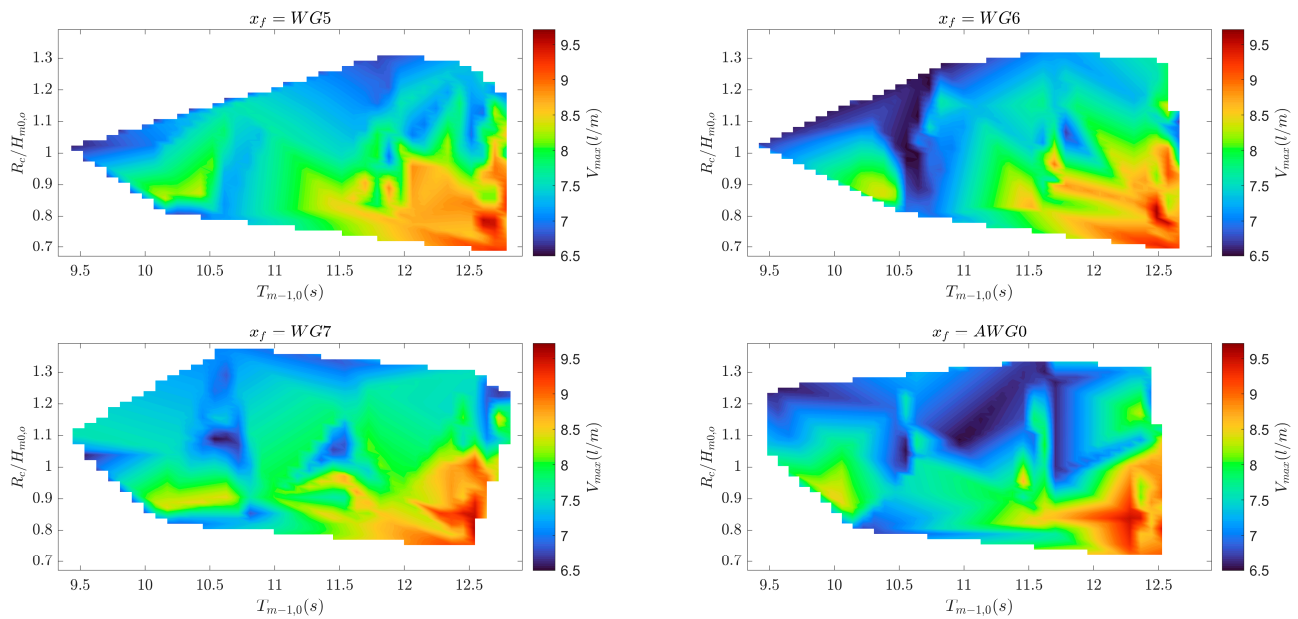


Figure 11. Variation in total overtopping volume (upscaled to a prototype and expressed in logarithmic scale) over the range of dimensionless freeboards and deep-water wave periods for each focus location.

In general, larger overtopping volumes were exhibited for larger periods and lower freeboards. In particular, the steeper the slope, the smaller the range of the wave period that maximized the volume (Figure 10). The vertical dike exhibited maxima for periods that were exceptionally long. Conversely, for the 1:2 dike slope and very low freeboards, the range of wave periods leading to maxima in overtopping volumes encompassed almost the entire range of periods tested. Upon examination of various focus locations (Figure 11), it can be observed that overtopping volumes exhibited elevated values for periods exceeding 11.5 s when combined with a dimensionless freeboard that was less than 1.

5.2. Dependence on Scaled Parameters

To enhance the comprehension of the relationship between the total overtopping volumes and scaled parameters, this section presents a detailed analysis of the impact of the equivalent slope (as defined in Equation (5)), dimensionless freeboard, and shallowness. The variation in V_{max}/V_0 on the relative freeboard and the equivalent slope, which is expressed as the cotangent of the angle with respect to the horizontal, is depicted in Figure 12; the results were gathered per focused location. Larger values of the equivalent slope resulted in larger overtopping volumes. As the foreshore was not varied during the experimental campaign, larger values of $\cot\delta$ actually corresponded to larger values of $\cot\alpha$. Hence, the mildest equivalent dike slope exhibited the largest overtopping, a fact that was already evident from Figures 3–6. This fact confirmed the results from IB2020, who demonstrated that a truncated beach's dependence of the volume on the offshore wave conditions and the slope angle. Here, the only difference from the IB2020 study is that the foreshore slope was replaced by an equivalent slope. Looking at the focused location, in general, we can conclude from Figure 12 that an x_f closer to the dike toe exhibited the largest volume.

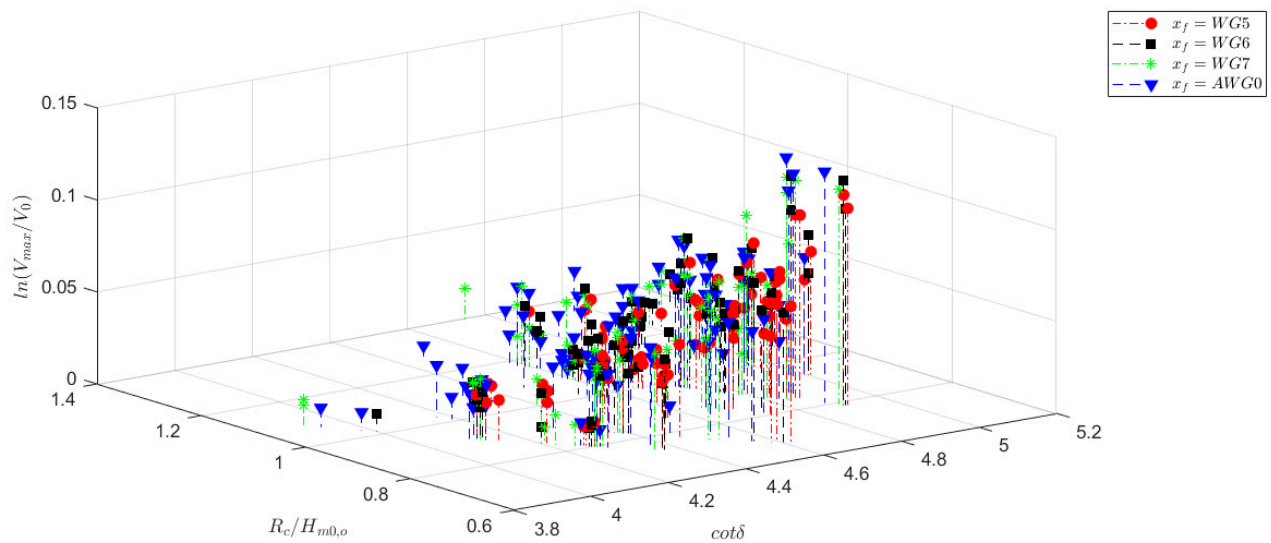


Figure 12. Variation in the dimensionless volume V_{max}/V_0 of the relative freeboard and equivalent slope. Results were gathered per focus location.

Figure 13 shows the dependence of the dimensionless volume V_{max}/V^* on the relative freeboard and shallowness. We used V^* (Equation (6)) rather than V_0 (Equation (3)) to include the influence of the slope (both of the foreshore and dike) in the analysis. A reduction in the local water level, to which an increase in the effective freeboard corresponded, led to small overtopping volumes. Nevertheless, especially for high values of shallowness, a lower freeboard did not necessarily determine the largest overtopping. While maxima in overtopping volumes were observed in proximity to the dike toe, it is crucial to acknowledge that in the majority of cases, waves had already broken prior to reaching that location. Consequently, the target focus wave amplitude was not actually achieved, and the celerity of each wave component was dominated by the local water depth rather than the period.

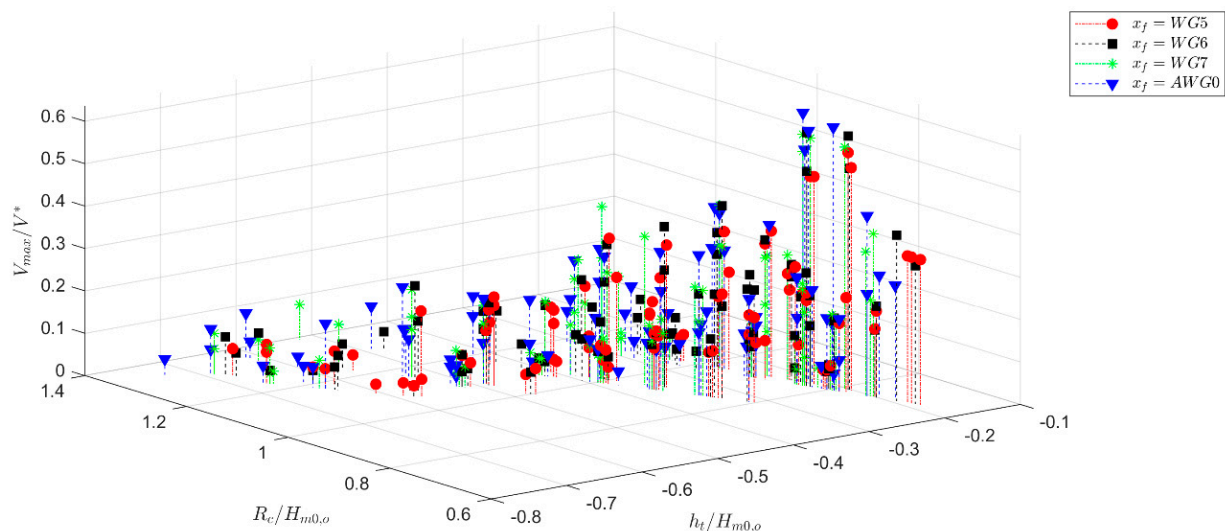


Figure 13. Variation in the dimensionless volume V_{max}/V^* of the relative freeboard and shallowness. Results were gathered per focus location.

Finally, an attempt was made to collect all data, including different slopes, wave conditions, and water depths, in a dimensionless form. This was performed in order to achieve a general interpretation of the maximization of the overtopping volume as a function of the focus phase and location. First of all, considering that the local water depth was taken into account for the definition of the equivalent slope, the results in terms

of V_{max}/V^* were plotted and are shown in Figure 14. It is evident that clusters can be clearly identified along vertical stripes. The dimensionless volume was maximized for specific bands in X and for phases between 0° and 90° , which is in accordance with the results previously presented. Peaks are still noticeable around ϕ equal to 180° but lower in magnitude. To confirm these results, in terms of a general interpretation of the data, including the effects of local water depth and dike slope, the same volumes were scaled on V_{L21} (see, Equations (16) and (17)), which also explicitly considered the effect of the relative freeboard. The results are depicted in Figure 15. The analysis indicated that the greatest overtopping volumes, adjusted in accordance with specified parameters, were observed at $X = 0.32$, with ϕ ranging between 0° and 90° . A secondary band exhibiting maximal volumes became apparent at $X = 0.76$. Additionally, discernible peaks were observed at focus phases of 180° and 270° for $X = 1.1$. The application of V_{L21} to scale the volumes enabled the results to be clustered together, thus reducing the scattering of data and facilitating a more immediate interpretation.

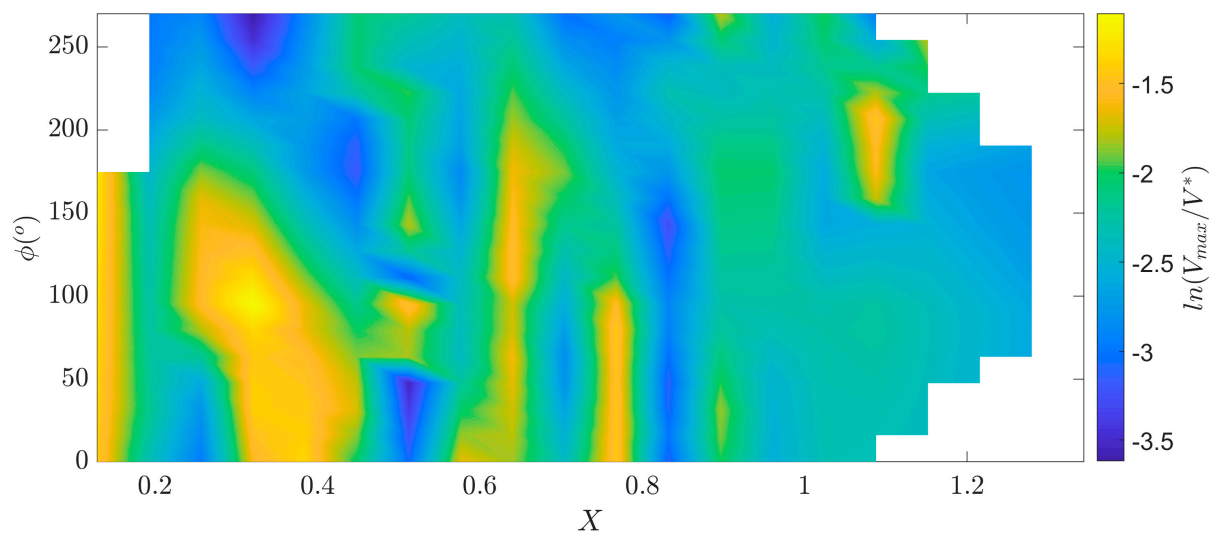


Figure 14. Variation in non-dimensional total overtopping volume (V_{max}/V^*) over the range of non-dimensional focus locations, X , phases (at focus), and water levels tested for all tests.

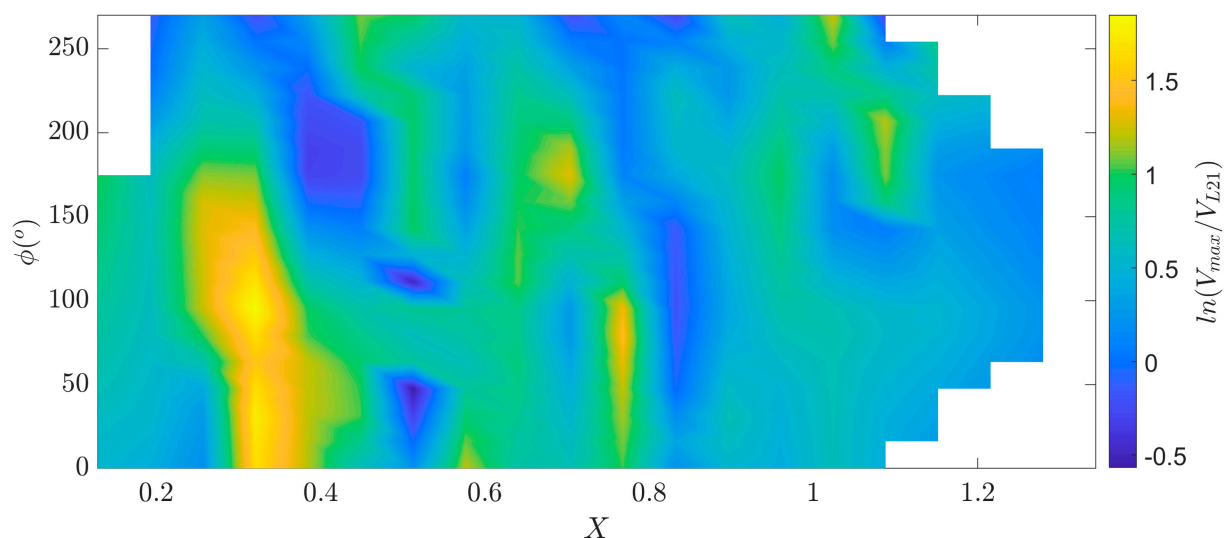


Figure 15. Variation in non-dimensional total overtopping volume (V_{max}/V_{L21}) over the range of non-dimensional focus locations, X , phases (at focus), and water levels tested for all tests.

6. Conclusions

In this study, we investigated wave overtopping volumes using focused wave groups on smooth dikes with an emerged toe. The main objective was to study how the volumes associated with maximum wave height values in a random sea state depended on the range of focus locations and phases. Providing precise guidance on how to maximize wave overtopping for a given sea state and structural layout would be beneficial in experimental practices where focused wave groups can be used instead of long time series of irregular waves. In fact, the use of focused wave groups offers several advantages, including increased repeatability, improved measurement capabilities, and better resolution of models used to investigate significant wave interactions.

Three dike slopes (1:2, 1:0.5, and vertical), in combination with a rather steep foreshore (1:6.3) and seawall emerged toe, were tested. The results showed that larger overtopping volumes were measured for the mildest dike slope, as expected. In general, overtopping volumes increased when the wave period became longer. However, the steepest dike was the most sensitive to the variation in the wave period. The longest period tested yielded the greatest overtopping volumes. Buffers where the volume was maximized were identified for the 1:2 slope. However, the results for the other two slopes were somewhat challenging to interpret due to the more intense and complex WSIs in the case of steep dikes, as well as the limited amount of available data, which made any analysis only moderately accurate.

Our findings revealed that the location of the focus point and the phase angle at focus were critical factors affecting wave energy concentration and subsequent overtopping volumes. Optimizing the focus location near the seawall enhances wave energy concentration towards the structure, leading to increased overtopping rates. Additionally, variations in the phase angle result in changes in wave characteristics, directly impacting overtopping volumes. By manipulating these parameters through small-scale physical model tests, we were able to observe their direct impact on overtopping responses.

Yet, the focus location and phase exhibited distinct influences on wave structure interaction. The phase angle at the point of focus assumed paramount importance in configuring the wave's characteristics, such as asymmetry, and the spatial distribution of constituent waves within the group. Although frequently disregarded in empirical forecasts of cumulative overtopping volumes during random sea states, phase data assume significance in optimizing responses for singular extreme events [15,40–42].

The focal point assumes a pivotal role in delineating the dispersion patterns of focused wave groups as they approach and undergo breaking along the shoreline. Alignment of the focus location proximate to the dike tends to accentuate the concentration of wave energy, thereby engendering notable effects of wave overtopping. Contrariwise, if the focus location lies offshore from the dike, it facilitates dispersion prior to reaching its location, thereby mitigating potential overtopping effects. It is crucial to emphasize that in the present study, it is possible for waves to break before reaching the target focused location. Consequently, the wave groupness may be affected, as the assumption that all wave components come into phase at the target focused location may not be met. Nevertheless, it was deemed highly interesting to explore the response of coastal structures in extremely shallow water conditions, which are quite common worldwide. This is despite the fact that a linear approximation of the focused wave group generation and propagation was employed.

To study the dependence of overtopping volumes on focus location and phase, for different hydrodynamic conditions, water levels, and dike slopes, different scaling for the maximum volumes were analyzed and compared. Starting from the volume flux defined by IB2020, this research revealed that more complex scaling, including the influence of both the foreshore and local water depth, helps to comprehend complex wave structure interaction, despite the wide variation in data in the parameter space. Considering three dike slopes in combination with a rather steep foreshore and seawall emergent toe, this study revealed that dimensionless volumes are in general maximized for focus phases of 0° and 90° if the focus location is placed at about one-third of the offshore wavelength from the dike toe. Phase angles of 180° and 270° lead to the smallest volumes, in general. These

findings confirmed that wave phasing, often disregarded in the assessment of coastal risk associated with overtopping events, plays a fundamental role and can lead to important differences in maximum volumes, even for the same deep-water wave conditions.

To summarize the main findings of the presented research for the design of experimental campaigns, it can be concluded that wave overtopping is maximized for focus locations at the dike toe or equal to one-third of the deep-water wavelength, combined with focus location phases between 0° and 90° . This eases the definition of wave conditions necessitating testing in experimental or numerical flumes. According to [43], the design wave height for wave–structure interaction, equal to 1.8–2 times the significant wave height, should be assessed at a dike toe or at a distance from it equal to five times the significant wave height. Based on this, in combination with the outcomes of the present research, it can be inferred that the maximum wave height used for the wave overtopping assessment of extreme individual overtopping events should be defined between the dike toe and $1/3 L_{m-1,0,0}$, as the wave components are focused and the wave shape is maximized at these locations.

In conclusion, this experimental study on wave overtopping volumes using focused wave groups provides valuable insights into the complex interplay between wave characteristics and coastal structure responses. The findings highlight the significance of focus location and phase angle in influencing overtopping behavior and demonstrate the advantages of using focused wave groups for studying coastal engineering phenomena.

It is essential to consider this study's limitations, such as investigating only one foreshore slope, analyzing dikes with emerged toes only, and utilizing first-order generation of focused wave groups. Future research will involve a more in-depth analysis of the influence of water levels by implementing corrected second-order generation for bound-long waves and examining the effects of wave setup on wave overtopping prediction [44,45]. Additionally, further analysis will be carried out to explore the combined effects of multiple factors, including wave height, period, water depth, and foreshore slope, in order to derive a semi-empirical expression for wave overtopping volumes.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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