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Numerical Simulation of Wave Run-Up on Coastal Structure with Hexaloc Armour Units based on the SPH Method

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Abstract

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Coastal abrasion and erosion pose significant threats to Indonesia's shorelines, necessitating reliable protection such as rubble-mound breakwaters. Accurate prediction of wave run-up is critical, as crest elevation directly determines structural safety. Conventional empirical formulae, primarily derived for riprap, often fail to account for the hydraulic performance of interlocking, highly porous units like Hexaloc. This study investigates wave run-up on Hexaloc-armoured breakwaters using the Smoothed Particle Hydrodynamics (SPH) method implemented in DualSPHysics to support more efficient crest level design. A two-dimensional numerical flume was developed for single- and double-layer Hexaloc configurations subjected to regular waves. Results show that non-dimensional run-up (Ru/H) increases with the Iribarren number. SPH simulations yielded Ru/H values of 0.56–1.66 for single-layer and 0.63–0.86 for double-layer arrangements. These results were systematically lower than Ahrens′ empirical predictions (1.59–2.39), reflecting the influence of armour thickness and permeability on energy dissipation. Strong correlations between SPH data and Ahrens′ formulation were obtained ($R^2 = 0.8551$ for single-layer; $R^2 = 0.9238$ for double-layer), indicating the numerical model accurately reproduces physical trends while revealing Hexaloc′s superior performance over conventional riprap. These findings suggest that Hexaloc armour can significantly reduce required crest elevations, leading to more cost-effective designs. Furthermore, the study confirms that SPH modelling provides a reliable tool for the optimization of innovative coastal armour units.

1. Introduction

The coastline is a dynamic boundary between land and sea that is continuously modified by natural processes and human activities. Changes in shoreline position are mainly governed by sediment transport, longshore currents, wave action, and coastal land use [1]. When sediment supply dominates, the coastline progrades seaward, whereas during abrasion, wave-induced erosion causes landward retreat [2]. These two processes are intrinsically linked, as erosion in one segment of the coast can contribute to accretion in another [3]. In Indonesia, coastal abrasion has become a critical issue, particularly along densely populated and low-lying coastal zones, where ocean waves drive progressive shoreline retreat and threaten infrastructure and livelihoods [4]. These conditions necessitate the construction of coastal protection structures to stabilise the shoreline and mitigate wave impacts. Among these, rubble-mound breakwaters are widely applied to reduce incident wave energy before it reaches the shore, either as shore-attached structures that protect harbour basins or as detached breakwaters that help to control erosion [5]. The stability and effectiveness of such structures are strongly controlled by their response to wave loading, especially under extreme conditions [6].

In breakwater design, the accurate estimation of wave run-up height is a key parameter because it directly affects crest freeboard, overtopping rates, and consequently the safety of the area landward of the structure [7]. Wave run-up occurs when incident waves climb up the slope or armour layer of a coastal defence structure and reach a maximum vertical elevation above the still water level [8]. The safety of a breakwater is determined by the elevation of the structure, which must be higher than the run-up value and the permitted wave overflow. Previous studies related to run-up measurement have employed various methods. In laboratory tests on a 1:6 slope, it was found that the run-up velocity exceeded the 2% threshold ($u_{2\%}$) reaching 1.39 for the natural spectrum and 1.55 for the Texel Marsen Arsloe (TMA) spectrum. In addition, the thickness of the water layer passing over the top of the structure at a 2% exceedance condition ($c_{h,2\%}$) was recorded at around 0.33, indicating the significant contribution of turbulence and aeration to the run-up and overtopping characteristics of the breakwater [9]. Such findings underline that run-up is not only a geometric response but is also influenced by complex hydrodynamic processes.

At the broader scale, climate change is expected to exacerbate coastal erosion and increase design demands on coastal protection. A systematic review of more than 200 global case studies showed that a projected sea-level rise of 0.3–1.0 m by the end of this century could accelerate land loss by 20–40% in low-lying deltaic regions [10]. A further synthesis of 95 case studies on coastal hydrodynamics and erosion demonstrated that short waves with periods of 5–8 s can drive substantial sediment transport, resulting in shoreline retreat rates exceeding 5 m/year in high-energy environments [11]. These studies emphasise that future coastal protection must be designed to withstand higher water levels and potentially more energetic wave climates. They also highlight a methodological trade-off: field observations provide realistic data but are expensive and spatially limited, whereas numerical models offer greater flexibility and scenario-testing capability but require rigorous validation against measurements. This motivates the integration of numerical modelling and observations in coastal morphodynamical and structural response studies.

Regarding coastal protection structures, geometric design guidelines for berm breakwaters have been developed through extensive laboratory experiments. These studies yielded empirical equations to predict the stability of armour layers and indicated that berm structures with milder slopes exhibit greater resistance to large wave run-up and overtopping [12]. However, most of these formulations were developed for conventional rock or simple concrete armour and remain constrained by laboratory conditions, so their direct field application often requires calibration. More recently, numerical methods have been increasingly used to analyse wave interaction with rubble-mound breakwaters. The Smoothed Particle Hydrodynamics (SPH) method has been applied to simulate wave overtopping and armour layer response [13]. For example, DualSPHysics simulations have reproduced overtopping discharge on rubble-mound breakwaters with deviations of less than 15% relative to experimental data, particularly for high waves and permeable structures [14], although computational cost remains a limitation for large domains and long-duration events [15]. In parallel, CFD-based Reynolds Averaged Navier Stokes (RANS) models have been employed to estimate wave run-up on sloping breakwaters, achieving mean errors below 10% for run-up heights on 1:2 slopes and demonstrating robust turbulence modelling capabilities, yet still facing challenges in capturing extreme overtopping with very large runoff volumes [16].

Despite this progress, most empirical run-up formulations and many numerical studies have been developed for conventional rubble-mound structures armoured with rock or standard concrete units. Interlocking concrete armour systems such as Hexaloc exhibit higher porosity, complex flow pathways, and different energy dissipation mechanisms compared with traditional riprap, which may lead to substantially different run-up behaviour. However, quantitative data and validated numerical models for wave run-up on Hexaloc armoured breakwaters remain limited, particularly regarding the influence of armour configuration (e.g. single versus double layers) under varying wave conditions. This gap is critical in the context of climate-driven increases in sea level and wave loading, where accurate run-up estimation is required to optimise crest elevation, ensure structural safety, and avoid overly conservative designs.

This study advances the state of knowledge by examining wave run-up on Hexaloc armoured breakwaters, a topic largely overlooked in previous run-up and overtopping research that has focused on conventional rubble-mound structures. Unlike empirical formulations such as Ahrens′ equation, which were derived for low-porosity riprap, this work provides the first systematic SPH-based quantification of run-up behaviour on a highly porous interlocking armour system and directly evaluates its deviation from classical predictions. Furthermore, the analysis of single- and double-layer Hexaloc configurations introduces a new perspective on how armour-layer permeability and thickness influence run-up dynamics, offering design-relevant insights not available in earlier studies.

Therefore, this study investigates wave run-up on rubble-mound breakwaters armoured with Hexaloc units using the Smoothed Particle Hydrodynamics (SPH) method implemented in DualSPHysics, with the aim of improving run-up prediction for innovative armour systems and supporting more efficient crest level design. The breakwater geometry is generated using CAD software and represented as a sloping structure with Hexaloc armour in single- and double-layer configurations. Numerical simulations are performed in a two-dimensional flume under a range of regular wave conditions characterised by different wave heights, wave periods, still water levels, and slope angles. The resulting non-dimensional run-up is then compared with established analytical and empirical formulations, particularly Ahrens′ equation, to assess the ability of SPH to reproduce classical riprap-based run-up trends while capturing the specific hydraulic response of Hexaloc armour. The outcomes of this research are expected to improve understanding of how wave and structural parameters control run-up on interlocking units, provide more reliable guidance for the design of Hexaloc armoured breakwaters, and clarify the advantages and limitations of SPH based modelling as a tool for coastal structure analysis.

2. Method

This study focuses on analyzing wave run-up on rubble-mound coastal structures with Hexaloc protective layers under irregular wave conditions. The research data were obtained through literature studies and digital geometry modeling using CAD software, which were then integrated into DualSPHysics software.

2.1. Hexaloc Armour Unit

In coastal protection structures, one of the main components is protective rock layers. This element functions as the outer layer that absorbs wave energy before it reaches the land. Protective layer rocks, also known as armor units, come in various types such as dolos, tetrapods, A-jacks, and others. Armor units are typically made of concrete with variations in shape that allow for better interlocking compared to ordinary rocks, thereby enhancing the stability of the structure [17].

Various countries have developed artificial stones as alternatives to natural stones for coastal protection layers, with different shapes and levels of stability. In addition to countries in Europe and America, Indonesia has also developed a new type of artificial stone called Hexaloc. The Hexaloc armor unit shares the same form as the A-Jack and hexapod. The Hexapod was introduced in the United States in 1959 [18], whereas the A-Jacks were developed in the United States in 1998 [19]. The legs of the unit are designed with a circular taper. The A-Jacks are formed by two identical components combined into a single unit, resulting in six legs extending from a filleted central hub, each with a square cross-section. In contrast, the Hexaloc consists of six legs with a hexagonal cross-section that converge at a single joint without a filleted hub [20]. Detailed images can be found in Figure 1 and Table 1.

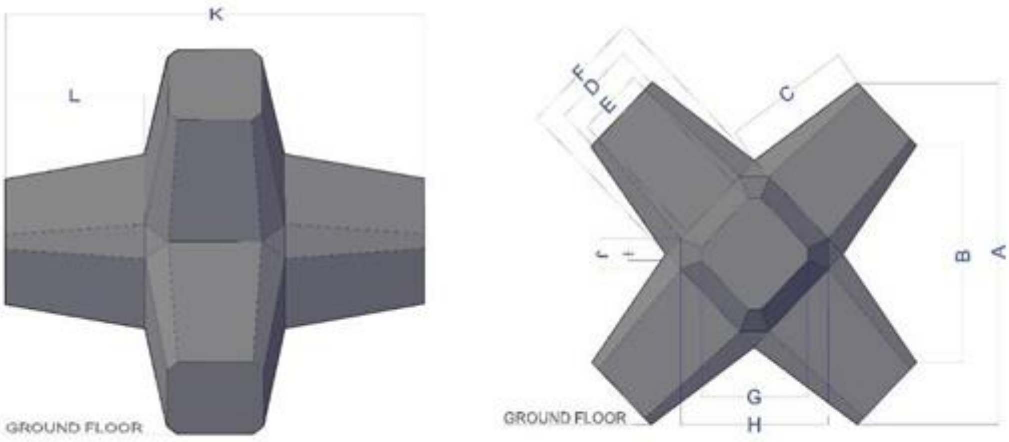


Figure 1. Systematic methods.

Table 1. Typical Hexaloc Dimension.

Symbol	A	B	C	D	E	F	G	H	I	J	K	L
Length (mm)	2106	1340	823	542	429	812	687	961	79	191	2437	808

2.2. Run-up and Irribaren Number

When waves hit a structure, the momentum carried by the waves pushes the water to creep up the surface of the building. The vertical height reached by the wave is referred to as the wave run-up [21]. The wave run-up value is very crucial in the design of coastal protection structures, as it determines the elevation of the structure's crest [22]. Wave run-up is influenced by various factors, including the shape and slope of the structure, the degree of surface roughness, the depth of the water around the base of the structure, and the characteristics of the waves hitting the water depth around the base of the structure, and the characteristics of the waves impacting the structure. Wave run-up is divided into two types: average run-up, which is the average height of the run-up of all waves, and 2% run-up, which is the average of the highest 2% of run-up from 100 observed waves [23]. Breaking waves can be identified using the Iribarren number (ξ) or surf similarity parameter [24]. Below are the equations used to calculate wave run-up.

$$\xi = \frac{\tan\alpha}{\sqrt{\frac{2\pi H_s}{gT^2}}} \tag{1}$$

where, ξ is the Irribaren number, α is the structure slope angle, H_s is the significant wave height, g is Earth's gravity, which has a value of 9.8 m/s^2, and T is the wave period.

Several researchers have proposed formulas to estimate wave run-up. Mase, through laboratory experiments on smooth and impermeable slopes with irregular waves, derived an empirical equation to predict maximum run-up applicable for slopes ranging from 1/30 to 1/5 and wave steepness between 0.007 and 0.07 [25]. The following formula is derived from the study.

$$\frac{R_{max}}{H_0} = 2.2{\xi_0}^{0.77} \tag{2}$$

Douglass investigated wave run-up by removing the beach slope factor from the formula. He argued that slope estimation is difficult and does not significantly influence wave run-up; therefore, $\tan\theta$in the Iribarren number could be replaced with a constant [26]. The equation for calculating wave run-up is as follows:

$$\frac{R_{max}}{H_0} = \frac{0.12}{\sqrt{\frac{H_0}{L_0}}} \tag{3}$$

$$L_0 = \frac{gT^2}{2\pi} \tag{4}$$

where, R_{max} is the run-up maximum, L_0 is wavelength, and H_0 is wave height.

Therefore, Ahrens and Heimbaugh developed an upper-bound equation for the maximum run-up of irregular waves on riprap revetments (rough, permeable slopes), which was developed from 1:16-scale laboratory tests [27]. Run-up was defined as *green water* (excluding spray), and the prediction is given by:

$$\frac{R_{max}}{H_{mo}} = \frac{1.022\xi}{1 + 0.247\xi} \tag{5}$$

2.3. Smoothed Particle Hydrodynamics

Gomez-Gesteira et al. [28] describe Smoothed Particle Hydrodynamics (SPH) (Figure 2) as a mesh-free Lagrangian method widely applied in Computational Fluid Dynamics (CFD). In this approach, particles represent the fluid, interact with solid boundaries, and capture large deformations in domains with moving boundaries. Over time, the SPH model has evolved with ongoing refinements, achieving satisfactory levels of accuracy, stability, and reliability for engineering practice. The fluid is discretized into a set of computational particles, making SPH suitable for simulating a wide range of problems, including astrophysical flows, free-surface phenomena, and complex fluid mixing. By eliminating the need for a fixed mesh, SPH offers computational benefits compared to conventional CFD techniques [29]. In this method, continuous media are represented by particle ensembles, and when applied to fluid flows, the Navier–Stokes equations are solved at each particle location based on interactions with neighboring particles. These neighbors are determined using a distance-based kernel function defined by a smoothing length, either within a circle (2D) or a sphere (3D). At each timestep, physical quantities are updated for all particles, which then move according to the new values [30].

Figure 2. The difference between mesh and particle discretization of continuous free-surface flow [31].

2.4. DualSPHysics

DualSPHysics is an open-source solver specifically developed to address free-surface flow problems. It employs the Smoothed Particle Hydrodynamics (SPH) method and is optimized with hardware acceleration to compute particle motion within a simulation domain efficiently. Designed for practical engineering applications, DualSPHysics builds upon the SPHysics model and is implemented using C++ and CUDA codes. The SPH framework in DualSPHysics is structured around three sequential processes: Neighbour List (NL), Particle Interaction (PI), and System Update (SU) [30]. To obtain numerical results, users must follow a series of steps within the program, which are illustrated in the workflow diagram shown in Figure 3.

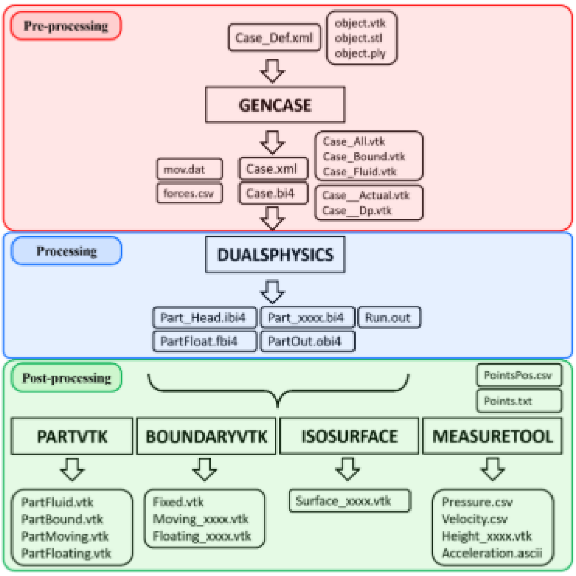


Figure 1. Workflow of the dualsphysics program [31].

2.5. Data Analysis

In this study, the authors employed a breakwater with a length of 1.53 m, a height of 0.75 m, and a width of 2 m, placed at a water depth of 0.65 m with a slope of 1:1.5. Three variables were varied in the experiments, namely wave height, wave period, and the number of structural arrangements. For further details, see Figure 4 and Table 2.

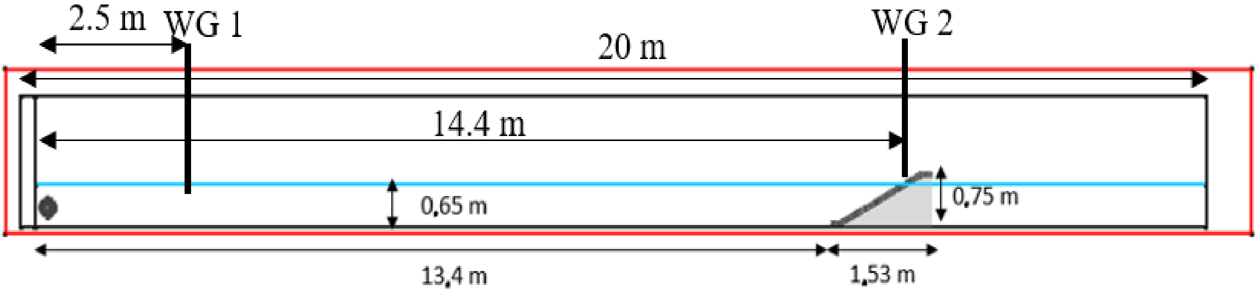


Figure 2. Test setup in DualSPHysics.

Table 2. Summary of wave conditions and armour-layer configurations for Run-Up simulations.

Variations	Number Of Layers	Wave Height (m)	Wave Period (s)
1	1	0.05	1.5
2		0.07	1.2
3		0.09	1.2
4		0.11	1.1
5		0.13	1.1
6	2	0.05	1.5
7		0.07	1.2
8		0.09	1.2
9		0.11	1.1
10		0.13	1.1

In this study, calibration and validation were performed by comparing the SPH-generated free surface elevation for regular waves with a reference second order wave profile reported by [32]. DualSPHysics implements the SPH method using discrete particles, allowing the particle spacing (dp) to be adjusted to control spatial resolution; smaller (dp) improves accuracy at the expense of higher computational cost. Considering the available hardware, (dp = 0.03) m was selected. Each simulation was run for 100 s, and wave gauges were positioned at (x = 2.5) m and (x = 14.4) m from the piston within the numerical wave flume.

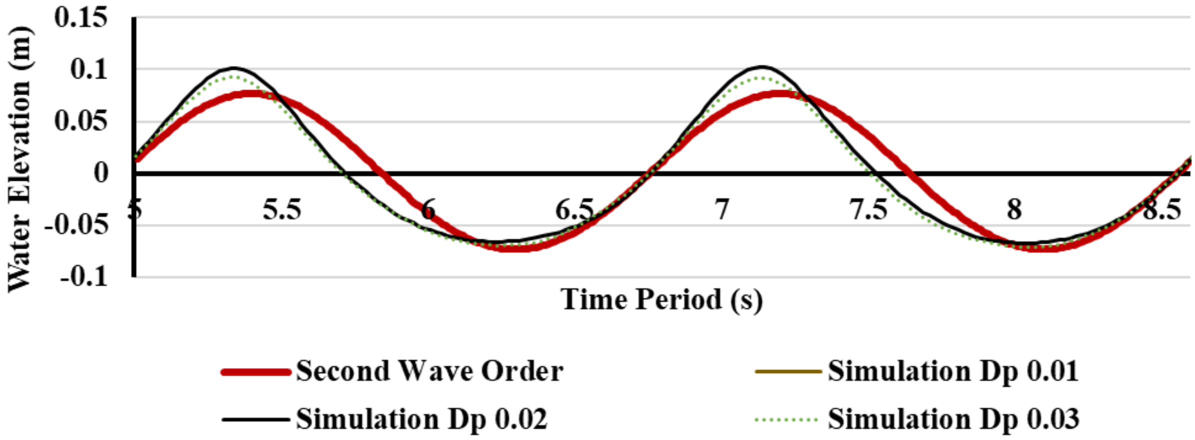


Figure 3. DualSPHysics model validation based on second wave order theory.

The reference second-order free-surface elevation $\eta_{ref}(t)$ was extracted from the published results in [32], where the nonlinear wave profile was reconstructed from second-order Stokes theory and validated against a numerical wave tank simulation. The SPH generated surface elevation $\eta_{SPH}(t)$ was obtained from the particle distance history recorded at the gauge location. Both signals were time-aligned and compared in terms of waveform shape, amplitude, and phase. The agreement between the two signals was quantified using the root-mean-squared error (RMSE), defined as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\eta_{SPH}(t_i) - \eta_{ref}(t_i))^2} \tag{6}$$

where $\eta_{\mathrm{SPH}}(t_i)$ represents the SPH free surface elevation at time t_i, $\eta_{\mathrm{ref}}(t_i)$ denotes the corresponding analytical second order elevation from [32], and N is the total number of sampled time steps. The comparison, presented in Figure 5, shows good correspondence between $\eta_{SPH}(t)$ and $\eta_{ref}(t)$, with a root-mean-squared error (RMSE) of approximately 0.07703, thereby justifying the use of this numerical wave tank configuration for the subsequent run-up simulations on the Hexaloc armoured breakwater.

3. Results and Discussion

3.1. Wave Run-Up Based on Mase′ s Theory, Douglass′ s Theory, and Ahren′ s Theory

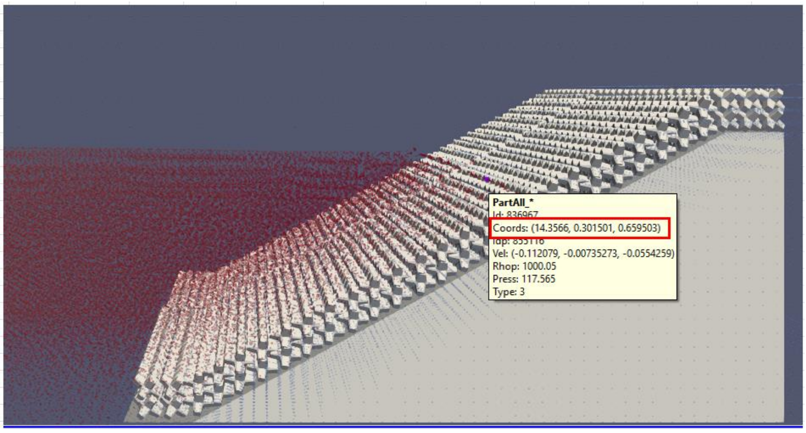
The analysis of wave run-up height on the non-overtopping breakwater structure in this study employs the theories of Mase′ s, Douglas′ and Ahrens′ approaches [25 -27], as outlined in Eq.(2), Eq.(3), and Eq. (5). These equations are considered the most relevant and applicable to the research context. The outcomes of this analysis will form the basis for validating wave run-up predictions using the Smoothed Particle Hydrodynamics (SPH) method. An illustrative calculation is provided, beginning with the determination of the wavelength (L) from Eq. (4) and the Iribarren number from Eq. (1). Table 3 presents the computed wave run-up values for each variation tested on the breakwater structure.

Table 3. Wave run-up height (m) based on theory

Variation	Wave Height, H (m)	Wave Height Significant, Hs (m)	Wave Period, T (s)	Wavelength, L (m)	Iribarren Number, ξ	Ru/H Mase (1989) [25]	Douglass (1992) [26]	Ahrens (1988) [27]
1	0.05	0.049	1.5	3.514	5.649	8.666	0.996	2.390
2	0.07	0.048	1.2	2.249	4.566	6.460	0.680	1.998
3	0.09	0.059	1.2	2.249	4.118	5.994	0.617	1.898
4	0.11	0.120	1.1	1.890	2.647	5.041	0.492	1.670
5	0.13	0.150	1.1	1.890	2.367	4.718	0.452	1.585
6	0.05	0.090	1.5	3.514	4.168	8.732	1.006	2.400
7	0.07	0.089	1.2	2.249	3.353	6.460	0.680	1.998
8	0.09	0.110	1.2	2.249	3.016	5.994	0.617	1.898
9	0.11	0.119	1.1	1.890	2.658	5.076	0.497	1.679
10	0.13	0.145	1.1	1.890	2.408	4.718	0.452	1.585

3.2. Wave Run-Up Based on SPH Method

This study employs a numerical model based on the Smoothed Particle Hydrodynamics (SPH) method, implemented in DualSPHysics. As an illustration, we present a simulation output of wave run-up height. The run-up is evaluated based on the maximum vertical coordinate reached by free-surface particles when the incoming waves interact with the breakwater. Particle positions in the x, y, and z directions are shown in Figure 6. In accordance with the definition of wave run-up, the reported run-up height is measured relative to the still-water level, specifically by subtracting the water depth from the maximum particle elevation. Table 4 presents the computed wave run-up values for each variation tested on the breakwater structure.



PartAll_*
Id: 836967
Coords: (14.3566, 0.301501, 0.659503)
Idp: 835116
Vel: (-0.112079, -0.00735273, -0.0554259)
Rhop: 1000.05
Press: 117.565
Type: 3

Figure 4. Free-surface particle positions extracted from the SPH simulation in the maximum run-up. The maximum vertical coordinate z_{max}relative to the still-water level is used to compute the run-up height.

Table 4. Wave Run-Up Height (m) Based on Numerical Simulation

Variation	Wave Height, H (m)	Wave Height Significant, Hs (m)	Wave Period, T (s)	Wavelength, L (m)	Iribarren Number, ξ	Wave Run-up, Ru (m)	Ru/H
1	0.05	0.049	1.5	3.514	5.649	0.081	1.597
2	0.07	0.048	1.2	2.249	4.566	0.069	0.988
3	0.09	0.059	1.2	2.249	4.118	0.086	1.018
4	0.11	0.120	1.1	1.890	2.647	0.080	0.715
5	0.13	0.150	1.1	1.890	2.367	0.084	0.637
6	0.05	0.090	1.5	3.514	4.168	0.078	1.560
7	0.07	0.089	1.2	2.249	3.353	0.070	1.001
8	0.09	0.110	1.2	2.249	3.016	0.079	0.932
9	0.11	0.119	1.1	1.890	2.658	0.084	0.768
10	0.13	0.145	1.1	1.890	2.408	0.091	0.686

3.3. Validation Wave Run-up Based on Previous Theory

In this section, the results of numerical simulations using the Smoothed Particle Hydrodynamics (SPH) method as implemented in the DualSPHysics program will be validated against previous research. In Figure 7, the wave run-up (Ru/H) obtained from the numerical simulations using the SPH method will be plotted on a Ru/H graph against the Iribarren number, based on previous studies. In this graph, the grey plot, the riprap studied by Ahrens, will serve as a reference for validating the wave run-up results in this research.

In Figure 7 presents the relationship between relative run-up (Ru/H)and the Iribarren number (ξ)for different armour types, based on both numerical simulations and previous experiments. All curves exhibit an increasing trend of run-up with larger ξ, showing that more reflective wave conditions produce greater run-up. The impermeable rip-rap curve, as indicated by Ahrens, represents the highest values and serves as an upper bound. In contrast, SPH simulations (one- and two-layer configurations) produce lower values, reflecting the influence of permeability and turbulence. The single layer case yields slightly higher run-up than the double layer, consistent with its greater permeability.

Comparisons with other experimental studies further highlight the effect of material and geometry. Data compiled by M. A. Losada and L. A. Giménez-Curto show that Rip-rap (Gunbak) and quarry stone (Dai & Kamel) show intermediate value, while concrete units such as tetrapods (Jackson) and dolos (Wallingford) achieve the lowest run-up (< 1.0) due to their complex geometries and high porosity [33]. Overall, the figure confirms that armor layer permeability and geometry are critical factors controlling run-up. The SPH results align well with experimental data, supporting the reliability of this tool for evaluating the performance of coastal structures.

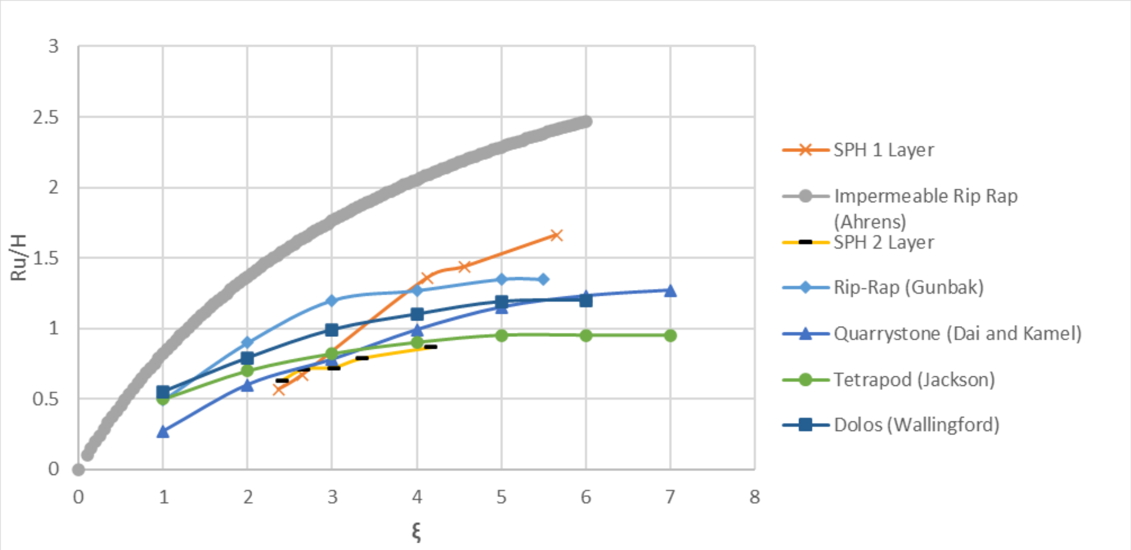


Figure 5. The influence of the iribarren number on the wave run-up

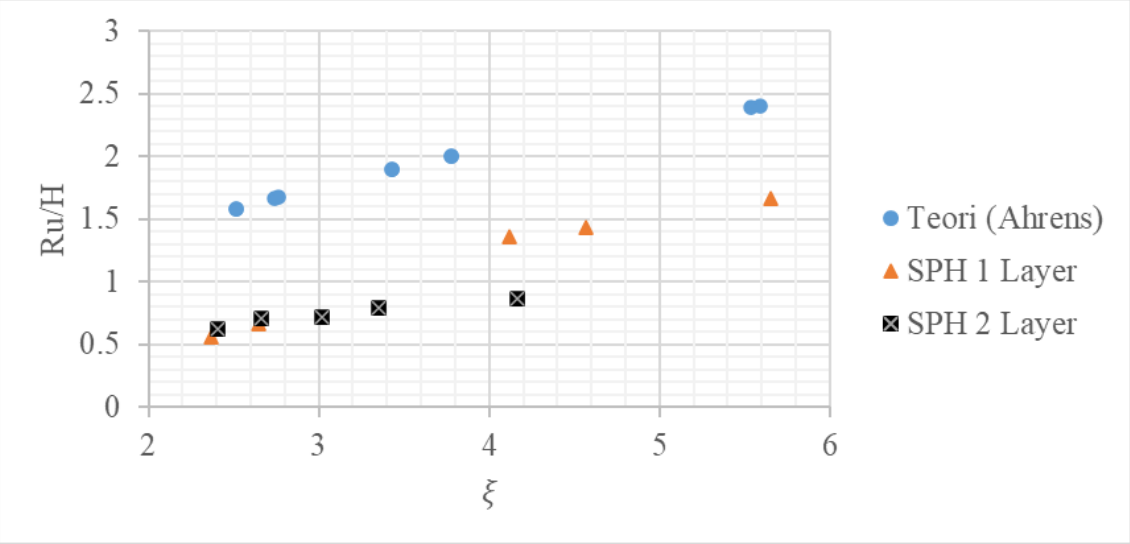


Figure 6. The relationship between wave run-up characteristics (Ru/H) and the Iribarren Number

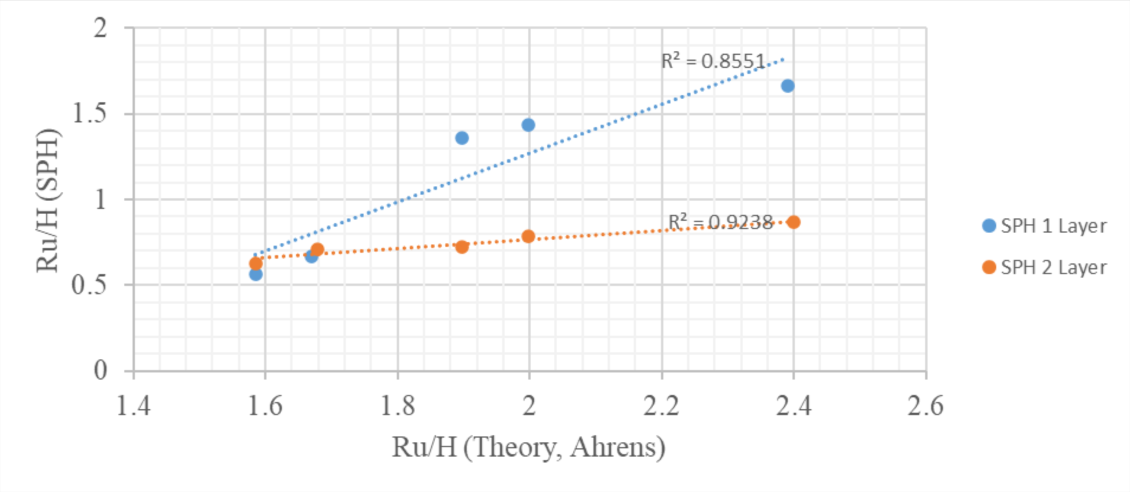


Figure 7. Run-Up relationship between numerical simulation results (SPH) and Ahren′ s Theory

In Figure 8, the relationship between wave run-up (Ru/H) and the Iribarren number, derived from both the SPH numerical method and the theoretical approach, shows a broadly similar trend. The figure indicates that as the Iribarren number increases, the incremental rise in Ru/H gradually decreases and eventually approaches a nearly stable condition. The numerical simulations performed using the Smoothed Particle Hydrodynamics (SPH) method are further compared and validated against the theoretical formulation proposed by Ahrens.

In Figure 9 shows the relationship between wave run-up characteristics (Ru/H)obtained from numerical simulations using the Smoothed Particle Hydrodynamics (SPH) method and the theoretical formulation by Ahrens. The Figure 9 presents a coefficient of determination of $R^2 = 0.8551$ for a single layer and $R^2 = 0.9238$ for a double layer, where values closer to 1 indicate stronger agreement between the two variables. This relatively high value suggests that the SPH numerical results and Ahrens′ s theory exhibit a strong correlation, indicating that both approaches produce comparable outcomes.

4. Conclusion

This study aimed to analyze wave run-up on rubble-mound breakwaters with Hexaloc armour units using the Smoothed Particle Hydrodynamics (SPH) method in DualSPHysics and to evaluate its reliability against existing theories. The results confirm that SPH simulations can reproduce wave run-up trends with good agreement to analytical and empirical models, particularly Ahrens′ s formulation. Relative run-up (Ru/H) was found to increase with the Iribarren number $(\xi = 2.36 - 5.64)$ for single layer, $(\xi = 2.40 - 4.16)$ for double layer and to stabilize at higher values, with SPH results ranging from 0.56 – 1.66 for single layer and 0.63 – 0.86 for double layer compared to theoretical predictions of 1.59 – 2.39. The comparison highlights that armour configuration influences run-up behavior, where single-layer Hexaloc produces higher run-up than double layers due to greater permeability, and armour geometry and arrangement play a key role in dissipating wave energy and reducing run-up. The strong correlation between SPH results and theory $(R^2 = 0.8551)$ for single layer, $(R^2 = 0.9238)$ for double layer and demonstrates that the SPH method is a reliable numerical tool to support the design of breakwaters, providing practical benefits for achieving both structural safety and cost efficiency.

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