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# Estimation of regular wave run-up on slopes of perforated coastal structures constructed on sloping beaches

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ABSTRACT

This study was carried out to investigate the regular wave run-up phenomenon on smooth slopes of perforated coastal structures constructed on sloping beaches and the various parameters that affect wave run-up. Experiments were conducted using various hydraulic and structural parameters. The relative coastal structure distance, relative depth, relative wave height, beach slope, coastal structure inclination, and surf similarity parameter were found to be positively correlated to the relative wave run-up. The wave steepness and coastal structure perforation percentage were found to be negatively correlated to the relative wave run-up. The results also show that the coastal structure perforation percentage plays a dominant role in the attenuation of short waves but a less significant role in the attenuation of long waves. The quantitative analyses were performed using multiple additive regression trees (MART) and multilayer perceptron neural networks (MLP) methods. The results indicate that the MART method's prediction accuracy and avoidance of over-fitting were superior to those of the MLP method. The percentage improvement in the root mean square error of the MART model over the MLP model in predicting relative wave run-up was 57.56%. The analysis results suggest that MART-based modeling is effective in predicting wave run-up.



## 1. Introduction

The interactions between waves and coastal structures cause water to rise above the level of incoming wave crests. When this phenomenon occurs near the up-wave face of a coastal structure, it is known as run-up. Wave run-up is one of the most important factors in the design of coastal structures exposed to wave attack. Seawalls, revetments, and sea dikes are typically designed so that little or no wave run-up overtops the structure. Accurate estimation of the maximum wave run-up can lead to more economical designs. Furthermore, beach processes, such as beach/dune erosion and storm flooding, are partly related to wave run-up. Several formulae have been developed to predict wave run-up. The value of a run-up formula lies not only in its ability to predict wave run-up and its convenience of use but also in the insights that examination of its terms and coefficients provide into the nature of the physical processes.

A number of theoretical and experimental studies of wave run-up on uniform slopes have been conducted in the past, but an exact mathematical model or analytical equation for predicting wave run-up on linear slopes has not yet been developed, because of the complexity of the run-up phenomenon. The contributions of Granthem (1953), Saville (1955, 1956, 1958), Savage (1958), and Le Mehaute et al. (1968) are among the earlier investigations of wave run-up. These researchers measured wave run-up caused by regular wave trains impinging on various types of smooth and rough sloping structures, composite slope structures and other variations (stepped, re-curved, etc). The run-up results were plotted as functions of various wave parameters and structure slopes, but no design formulas were given. Saville (1958) showed that the experimental results for uniform slopes could be used to predict run-up on composite slope structures with reasonable success. Since its first appearance in the literature, Saville's composite slope method has gained wide acceptance and is included in the US Army Shore Protection Manual (1984). Taylor et al. (1980) eliminates the disadvantages of Saville's composite slope method by using a smooth functional representation of the profile geometry rather than the piecewise linear segmentation proposed by Saville. Gopalakrishnan and Tung (1980) developed a numerical model based on the Galerkin finite element method to analyze wave run-up on moderate slopes. Kobayashi et al. (1987) adopted a modified explicit dissipative Lax–Wendroff finite difference method to predict wave reflection and run-up on rough slopes. Various studies have been conducted on wave run-up, and several empirical formulae and design curves have been developed based on the results of laboratory experiments. To predict regular waves on an impermeable slope, Thompson (1988) applied the continuity equation and the horizontal momentum equation used by Kobayashi et al. (1986, 1987) to predict regular waves on an impermeable slope.

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Another approach to describing wave run-ups on a beach or other structures is to develop and apply numerical models that predict temporal and spatial variations in run-up elevations. A depth-averaged nonlinear shallow water equation (Kobayashi, 1989; Raubenheimer and Guza, 1996; Raubenheimer, 2002) is widely used to simulate wave run-ups in engineering practice. Lynett et al. (2002) and Nwogu and Demirbilek (2010) developed a numerical model for simulating wave run-ups that combined Boussinesq equations with a dry–wet moving boundary technique. Hsu et al. (2012) reported the development of a high-order numerical model for regular waves based on the second-order nonlinear Boussinesq equations derived by Wei et al. (1995). They found that the numerical results, laboratory observations, and previous datasets were in good agreement.

The uncertainties associated with empirical formulas inevitably increase the factor of safety required and the construction cost (Kim and Park, 2005). Various studies have recently been carried out to develop more accurate models for wave run-up. Wei et al. (2010) used a back-propagation (BP) network with one hidden layer to calculate solitary wave run-up. Erdik and Savci (2008) proposed a run-up model based on the Takagi–Sugeno fuzzy model approach. Erdik et al. (2009) improved the accuracy of wave run-up prediction for rubble mounds using an artificial neural network (ANN) approach. They found that the ANN technique yielded more accurate results and that the degree of accuracy can be affected by the structure of the ANN. Both Erdik and Savci (2008) and Erdik et al. (2009) developed their models using an experimental data set published by Van der Meer and Stam (1992). Bonakdar and Etemad-Shahidi (2011) investigated the performance of the M5 model tree in predicting wave run-up on rubble-mound structures. The predictive accuracy of the model tree approach was found to be superior to that of Van der Meer and Stam's empirical formula.

Perforated structures are used worldwide to protect harbors and beaches from waves and currents attack. This type not affecting the seabed creatures, so it called friendly environmental structure. The phenomenon of wave run-up on smooth slopes of perforated coastal structures constructed on sloping beaches was investigated in this study. The effects of hydraulic and structural parameters, such as the relative wave height, wave steepness, bottom slope, location of the seawall relative to the average surf zone width, relative water depth, surf similarity parameter, and the percentage of perforation of structures and structural slopes, were investigated. Parametric run-up plots were prepared based on the experimental results. In addition to these results, this paper presents the design, implementation, and testing of a multiple additive regression trees (MART) model that can serve as a modern innovative technological approach to the prediction of wave run-up on the basis of experimental data, without reliance on a mathematical relationship to widen the range of application.

## 2. Background

The earliest study of the run-up phenomenon was a study on standing waves published by Airy (1845). He concluded that the wave run-up on a rigid vertical wall above the still-water level (SWL), $R$, equals the wave height, $H$. Isaacson (1950) suggested the following wave run-up formula for steep beach slopes, where $\beta$ is the beach slope angle, assuming total wave reflection.

$$\frac{R}{H}=\sqrt{\frac{\pi}{2\beta}} \tag{1}$$

This relationship does not include the effect of wave steepness. Thus, the equation is expected to be valid only for small wave steepness values.

Miche (1951) proposed the following equation for wave run-up based on linear wave theory:

$$\frac{R}{H}=\sqrt{\frac{\pi}{2\beta}}+\pi\frac{H}{L}\left(\frac{1}{\tanh\left(\frac{2\pi d}{L}\right)}\right)\left[1+\frac{3}{4\sinh^2\left(\frac{2\pi d}{L}\right)}-\frac{3}{4\cosh^2\left(\frac{2\pi d}{L}\right)}\right] \tag{2}$$

where $L$ is the wave length and $d$ is the water depth.

Saville (1956) and Whalin et al. (1971) proposed the following equation for wave run-up on small beach slopes for large wave steepness values:

$$\frac{R}{H}=\frac{\tan\beta}{\left(\frac{H_o}{L_o}\right)^{0.4}} \tag{3}$$

where $H_o$ is the deep wave height and $L_o$ is the deep water wave length.

For surging waves on a plane and impermeable slopes, Hunt (1959) simply recommended the following equation:

$$\frac{R}{H}\approx 3 \tag{4}$$

where $H$ is the wave height (assumed to be the deep-water wave height, i.e., $H\approx H_o$). Hunt's analysis of waves breaking on a slope resulted in the following dimensionally nonhomogeneous equation for the maximum run-up $R$:

$$\frac{R}{H}=2.3\frac{\tan\theta}{\sqrt{\frac{H}{T^2}}} \tag{5}$$

where $T$ is the wave period and $\theta$ is the structure slope angle. Recognizing that the coefficient 2.3 has units of $\mathrm{ft}^{1/2}/\mathrm{s}$, Eq. (5) can be expressed as a dimensionally homogeneous equation with the introduction of the gravity constant in imperial units, i.e.

$$\frac{R}{H}=1.0\frac{\tan\theta}{\sqrt{\frac{H}{L_o}}}\text{or}\frac{R}{H}=\xi_o \tag{6}$$

where the deep-water wavelength is given by $Lo=(gT^2/2\pi)$ and $\xi_o=\frac{\tan\theta}{\sqrt{\frac{H}{L_o}}}$ is defined as the deep- water Iribarren number (Iribarren and Nogales, 1949), also known as the “surf similarity parameter” (Battjes, 1974a). The parameter $\xi_o$ is often calculated using a finite-depth local wave height in the vicinity of the slope toe rather than the true deep-water depth, $H_o$. For example, $H$ is commonly specified in laboratory experiments as the wave height measured over the flat-bottomed portion of the wave facility before significant wave transformation occurs due to shoaling. In some cases,$H\approx H_o$ but this relationship is not always assured. For the purposed of this study, they assumed that $\xi_o$ was based on the local wave height at or near the toe of the slope rather than on $H_o$.

Most methods of predicting wave run-up on open-coast beaches are variations of the Hunt formula, which was proposed by Hunt (1959) and rewritten as follows by Battjes (1974b)

$$\frac{R}{H_o}=\frac{\tan\beta}{\sqrt{\frac{H_o}{L_o}}}=\xi \tag{7}$$

where $\xi$ is the surf similarity parameter (Iribarren number). Battjes (1974b) showed that the dimensionless run-up is typically equal to $\xi$ over the range from $0.1<\xi<2.3$ for regular waves acting on uniform, smooth, and impermeable laboratory beaches with slopes typical of many natural beach slopes.

Silvester (1974) suggested the following two empirical equations for non-breaking and breaking wave conditions:

$$R=2\eta_c A^* \text{ (for non − breaking waves)} \tag{8}$$

in which $\eta_c$ is the incident wave crest height above SWL and $A^*$ depends on the parameter $k=\frac{1}{\theta}\sqrt{\left(\frac{2\pi d}{L_o}\right)}$