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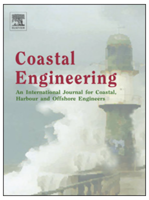

Run-up on vertical piles due to regular waves: Small-scale model tests and prediction formulae

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ABSTRACT

In wave-structure interaction, one of the most important phenomena clearly identified is wave run-up on offshore structures. In this study, wave run-up on a slender pile due to non-breaking regular waves is investigated by means of small-scale experiments performed in the 2 m-wide wave flume of Leichtweiss-Institute for Hydraulic Engineering and Water Resources (LWI) in Braunschweig, Germany. The test programme is designed to generate a comprehensive data set covering a broader range of wave conditions including not only deep and intermediate water conditions but also nearly shallow and shallow water conditions, which are missing in the available laboratory studies on wave run-up on piles. The relative wave height (H/h), relative water depth (h/L) and slenderness of pile (D/L) are identified as the key parameters governing the relative wave run-up (R_u/H). Based on these parameters, new formulae covering the range of tested conditions ($0.028 \le H/h \le 0.593$, $0.042 \le h/L \le 0.861$, $0.003 \le D/L \le 0.206$) are developed to predict regular non-breaking wave run-up on single piles using a combination of the M5 model tree and nonlinear regression techniques. Using statistical accuracy metrics such as agreement index I_a, squared correlation coefficient R^2 and scatter index SI, the performance of the developed formulae is evaluated. It is shown that the new formulae outperform the current formulae in predicting regular wave run-up on single piles. This success is in part due to the explicit account for the water depth in the new experiments and formulae. The proposed model is valid for a wider range of wave conditions and, therefore, more appealing for engineering practice compared to those available for the estimation of regular wave run-up.

1. Introduction

1.1. Importance of the study

Europe is the world leader in offshore wind power, with the first offshore wind farm built in Denmark in 1991. The design and construction of support structures for offshore wind turbines is one of the most challenging issues in civil engineering. One of the important issues in the design of offshore support structures (e.g. oil and gas platforms, offshore wind turbines and piers) is wave run-up. Wave run-up is referred to the vertical upward rush of water that occurs when an incident wave hits a partially immersed structure. It is an important parameter for the assessment of wave loads on surface-piercing offshore structures. Wave run-up height also plays an important role in designing the free board of offshore support structures.

A failure of an offshore structure would not only cause significant financial losses, but might also result in widespread environmental damages underlining the importance of the safe design of support structures. For example, the underestimation of wave run-up on a wind turbine's support structure in the Horns Reef 1 wind turbine park in Denmark led to damage to the structure (Lykke Andersen et al., 2011).

1.2. State of the art

Considerable studies have been dedicated to wave run-up on vertical piles, including a large number of analytical, experimental and numerical studies. Among the investigations on wave run-up on vertical piles, McCamy and Fuchs (1954) was one of the first researchers to study wave field around a vertical pile based on linear diffraction theory. The following formula was proposed for the calculation of surface elevation around vertical circular piles.

$$\eta(\theta) = \frac{H}{2}\sqrt{1+(2ka.\cos\theta)^2}\,\sin(\omega t - \psi) \qquad (1)$$

where η is the surface elevation, θ is the angle measured from the front centre of the pile, H is the wave height, k is the wave number, a is the radius of the vertical pile, ω is the angular frequency, t is time and ψ is

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defined as follow:

$$\psi = \tan^{-1}(2ka\cos\theta) \tag{2}$$

For the estimation of wave run-up R_u on the front side of a vertical pile, the following formula was proposed:

$$\frac{R_u}{\eta_{\max}} = \left(1 + (2ka)^2\right)^{-0.5} \tag{3}$$

The linear diffraction theory is valid only for small wave heights. This theory was also applied by Sarpkaya and Isaacson (1981) for the estimation of the wave surface elevation around vertical piles. Using different methods, diffraction theory was extended to the second order in some studies (e.g. Kim and Hue, 1989; Kriebel, 1990; Martin et al., 2001).

Based on the so-called velocity stagnation head theory, Hallermeier (1976) proposed a formula for the prediction of wave run-up on vertical piles. The idea behind the velocity stagnation head concept is that when a wave hits a structure, the kinetic energy of the water particles at the wave crest has to be converted into potential energy by rising a distance equal to $u^2/2g$ up the pile above the crest elevation. Based on this approach, the following formula was proposed for the prediction of wave run-up R_u on vertical piles:

$$R_u = \eta_{\max} + m\frac{u^2}{2g} \tag{4}$$

where η_{max} is the maximum wave crest elevation, m is an adjustment coefficient, u is the water particle velocity at η_{max} and g is the gravity acceleration. For long waves, in which wave kinematics are calculated using solitary wave theory, Hallermeier (1976) proposed m coefficient to be equal to 1.

Niedzwecki and Duggal (1992) studied wave run-up on vertical piles due to regular and irregular waves by means of small-scale laboratory tests. Wave run-up values were measured using spaced resistance type wave gauges which were placed directly on the surface of the tested pile with a diameter of $D = 0.114$ m. Based on the linear wave theory, the maximum wave-induced flow velocity was calculated at the still water level (SWL) which resulted in $m = 6.83$ and $\eta_{max} = H/2$. Niedzwecki and Huston (1992) proposed $m = 6.52$ and $\eta_{max} = 0.56H$ to alter the linear fit and proposed the following formula:

$$R_u = 0.56H + 6.52\frac{u^2}{2g} \tag{5}$$

Martin et al. (2001) also investigated regular wave run-up on a vertical pile ($D = 0.11$ m) by means of small-scale laboratory tests. They compared the results of the laboratory tests with different approaches. They found poor agreements between the results of the laboratory tests and those obtained from both linear diffraction theory and velocity stagnation head method. By means of small-scale laboratory tests, Mase et al. (2001) studied wave run-up of random waves on a circular pier installed on a uniform slope bottom; under various wave conditions and bottom slopes. They also derived a prediction formula for the run-up height $R_{u2\%}$.

De Vos et al. (2007) experimentally investigated wave run-up on vertical piles exposed to regular and irregular waves. Their tests covered only intermediate and deep water conditions. Wave run-up heights were measured using (i) the resistance-type wave gauges mounted around the pile ($D = 0.12$ m) with approximately 2 mm from the pile surface and (ii) video recording. They found out that due to the 2 mm distance between the wave gauges and pile surface, wave run-up is slightly underestimated for thin run-up layers, which are caused by the highest waves with very high run-up levels. As they stated, however, the video recording provided accurate measuring of wave run-up on piles. Lykke Andersen and Frigaard (2006) studied wave run-up on vertical piles due to regular and irregular waves by conducting small-scale laboratory tests. The wave run-up levels were measured using resistance-type wave gauges placed around the pile with approximately 2 mm from the pile surface. Their laboratory experiments were limited to intermediate water depth ($0.85 \leq h/L \leq 0.14$).

De Vos et al. (2007) used the velocity stagnation head theory (Eq. (4)) for the prediction of wave run-up on piles. For the case of regular waves, they reported that $m = 1$ results in the underestimation of wave run-up when the horizontal wave-induced flow velocity is calculated based on the linear wave theory. They also found out that the formula proposed by Niedzwecki and Duggal (1992) overestimates the wave run-up on a single pile. De Vos et al. (2007), however, concluded that $m = 1$ provides a reasonable estimation of regular wave run-up on vertical piles when the second order of Stokes theory is applied for the computation of horizontal flow velocity. Lykke Andersen et al. (2011) re-analysed the laboratory data of De Vos et al. (2007) and found out that stream function theory provides less scatter in predicting the adjustment coefficient, m compared to the second order of Stokes theory. They also stated that by increasing wave height to water depth ratio or relative wave height H/h, the adjustment coefficient m increases; i.e. wave nonlinearity affects wave run-up. Motivated by this implication, Peng et al. (2012) investigated numerically wave run-up on single piles. They found out that wave non-linearity significantly affects wave run-up heights. They showed, in fact, that wave run-up depends on Ursell number $Ur = HL^2/h^3$, which includes both H/h and h/L parameters. They also stated that wave run-up increases as the pile diameter D increases. They stated that their numerical model might not be valid for Ursell number larger than 70. According to the tested wave conditions and water depth, their study is limited to intermediate water depth and does not cover shallow water condition.

Ramirez et al. (2013) studied wave run-up of irregular waves on vertical piles by conducting large scale experiments in the large wave flume (GWK) of the Forschungzentrum Küste (FZK) in Hannover, Germany. The focus of their study was on the near breaking and breaking waves. The wave run-up events on the tested pile with a diameter of 0.56 m were recorded by a high speed video camera as they found out that the wave gauges placed around the pile underestimate wave run-up heights. They classified wave run-up heights in three levels, including green water layer (level A), thin layer of mixed water and air (level B) and maximum spray (level C).

Recently, Kazeminezhad and Etemad-Shahidi (2015) investigated regular and irregular wave run-up on vertical piles using the laboratory data sets of Lykke Andersen and Frigaard (2006), De Vos et al. (2007) and Ramirez et al. (2013). In contrast to the most of previous studies, in which wave run-up on vertical piles was estimated based on the velocity stagnation head theory, Kazeminezhad and Etemad-Shahidi (2015) estimated wave run-up height for non-breaking waves based on the non-dimensional wave parameters. They determined the ratio of wave height to water depth H/h and the ratio of the local wave height to deep water wave length H/L_0 as the governing parameters for the estimation of the relative wave run-up height R_u/H. Based on these two non-dimensional parameters and using a combination of the M5 model tree (M5MT) and nonlinear regression techniques, they proposed the following formulae for the prediction of regular wave run-up on vertical piles:

$$\frac{R_u}{H} = 0.76\left(\frac{H}{h}\right)^{0.15}\left(\frac{H}{L_0}\right)^{-0.055} \qquad \frac{H}{h} \leq 0.41 \tag{6}$$

$$\frac{R_u}{H} = 0.65\left(\frac{H}{L_0}\right)^{-0.055} + 3.2 \times 10^{-3}\left(\frac{H}{h} - 0.41\right)^{0.15}\left(\frac{H}{L_0}\right)^{-1.5} \qquad \frac{H}{h} > 0.41 \tag{7}$$