Coastal Engineering 121 (2017) 44–55

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Optimisation of focused wave group runup on a plane beach

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ARTICLE INFO

Keywords:
Runup
Focused wave groups
Wavemaker theory
Spurious error wave
Boussinesq numerical wave tank
Extreme waves

ABSTRACT

Insight is provided into focused wave group runup on a plane beach by means of laboratory wave flume experiments and numerical simulations. A focused wave group is presented as an alternative to an empirical description of the wave conditions leading to extreme runup. Second-order correction to the laboratory wavemaker generation signal is observed to remove about 60% of the sub-harmonic error wave that would otherwise contaminate coastal response experiments. Laboratory measurements of the wave runup time history are obtained using inclined resistance-type wires and copper strips attached to the beach surface. The numerical wave runup model is based on hybrid Boussinesq-Nonlinear Shallow Water equations, empirical parameters for wave breaking and bed friction, and a wetting and drying algorithm. After calibration against experimental runup data, the numerical model reproduces satisfactorily the propagation, shoaling and runup of focused wave groups over the entire length of the wave flume. Results from a comprehensive parametric study show that both measured and predicted maximum runup elevations exhibit strong dependence on the linear focus amplitude of the wave group (linked to its probability of occurrence), the focus location, and the phase of the wave group at focus. The results also demonstrate that extreme runup events owing to focused wave incidence cannot be characterised using spectral parameters alone. The optimal band of focus locations shifts onshore as linear focus amplitude of the incident wave group increases. Optimisation of phase and focus location leads to a maximum runup elevation at each linear amplitude, and, when generated using second-order corrected paddle signals, the maximum runup appears to approach saturation at very large focused wave amplitudes. This study therefore moves beyond simple wave focusing, and presents a focused wave group as a tool for investigating the relationship between extremes within an incident wave field and extreme wave runup.

1. Introduction

Coastal communities rely on sea defence structures for protection against flood inundation. Worldwide, the populations of such communities are increasing, while much coastal defence infrastructure is ageing [38]. Runup, the maximum elevation attained by seawater above the still water shoreline [43], has a primary influence on surf-zone sediment transport, beach levels and coastal erosion [61], wave overtopping of natural or artificial defence structures, and subsequent inland flooding. Storm-induced wave runup and its consequences are particularly sensitive to sea level rise [55,14,22,72,83] and climate variability [60]. Runup requires accurate estimation by coastal engineers and managers as part of routine coastal assessment studies.

Present understanding of wave runup on beaches and coastal structures is informed by field observations, physical experiments, and mathematical models. Such models and the empirical relationships derived from field/laboratory studies are used to predict extreme instances of runup. Runup and swash zone motions have been measured in field and laboratory campaigns using standard vertical wave gauges (e.g. [74,45]), non-intrusive altimeters (e.g. [9,29]), inclined resistance-type wires (see [21,58,27,32], among many others), pressure transducers (e.g. [30,32]) and interpretation of video records (see [30,59,71], among many others). More recently, lidar has been used for runup measurement in the field [10,2,1,17] and for measuring free surface elevations in certain large-scale experimental facilities [11]. A review of swash zone hydrodynamics, including the effects on beach morphodynamics, is provided by Brocchini and Baldock [13].

Laboratory experiments allow testing of wave processes under controlled conditions, often considering propagation in one horizontal dimension within a wave flume (e.g. [48,47,45,5,16]). Although the

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http://dx.doi.org/10.1016/j.coastaleng.2016.12.001
Received 11 January 2016; Received in revised form 22 November 2016; Accepted 12 December 2016

idealised geometries, relatively small model scales and simplified (regular or irregular) wave input typically used in laboratories may neglect certain physical processes observed in the field, laboratory experiments are useful tools for model validation and hypothesis testing. Numerical models often complement (and extend) laboratory or field experiments. Although recent advances in computational power have led to increasingly widespread use of advanced three-dimensional CFD models (such as the open-source OpenFOAM package, see [24,25]), more computationally efficient solvers for simplified models are better suited to collect extreme statistics from large numbers of incident waves. Depth-integrated wave-resolving flow models (e.g. [15,77,75,65]) are able to describe pre- and post-breaking waves, achieving an effective compromise between computational efficiency and realistic representation of the dominant physical processes affecting wave runup. Soldini et al. [67] found good agreement between their shallow-water model predictions and the empirical relationships of Stockdon et al. [71] and Vousdoukas et al. [80], and highlighted the effect of the beach profile on the maximum wave runup. Guza and Feddersen [20] demonstrate the effect of directional spread and frequency characteristics on significant wave runup, and recommend both characteristics be included in parameterisations of infragravity wave runup.

A key runup-related design parameter is the extreme runup, often defined as the vertical elevation exceeded by the largest 2% of the runup excursions ($R_{2\%}$). This extreme runup is often treated empirically for broken incident waves, and has been characterised using the Iribarren number (see [36,8]):

$$\zeta = \frac{\beta}{(H/L_0)^{1/2}}, \tag{1}$$

where β is the beach slope, H the wave height and L_0 the deep-water wavelength. Different expressions involving the Iribarren number have been developed using laboratory experimental results [36,47,79,23]. Hughes [34] used the (maximum depth-integrated) momentum flux parameter to obtain an empirical relation for a range of slopes. Field data investigations also determined empirical relations between the offshore wave conditions/beach geometry (not exclusively using the Iribarren number) and $R_{2\%}$ [21,28,50,61,71,80]. These empirical relationships, and others related to overtopping, form the basis of much coastal design [56]. Other studies on runup dynamics and swash spectra have been conducted by Raubenheimer et al. [58], Raubenheimer and Guza [57], Hughes and Moseley [32], Hughes et al. [33,31]. Blenkinsopp et al. [9] reviewed and assessed the applicability of the extreme wave parameterisations in the context of the BARDEX *II* project [49], finding that the bore height at collapse was an excellent predictor of the runup elevation in an irregular wave climate. Park and Cox [54] used a Boussinesq model to derive an empirical formula to account for storm surge conditions and the presence of beach berms/dunes.

Wave focusing has been the subject of field, numerical and experimental investigations, particularly in the context of rogue wave formation [42]. Baldock et al. [6] compared laboratory measured surface elevations and kinematics against linear theory and the second-order theory of Longuet-Higgins and Stewart [46]. Laboratory investigations by Johannessen and Swan [40] demonstrated that directionality had a significant effect on wave group focusing, in agreement with previous numerical simulations by Johannessen and Swan [39]. Gibson and Swan [19] analysed theoretical predictions of Bateman et al. [7] to study changes in a wave spectrum near to a focusing event (in both unidirectional and spread sea states), and discussed the implications for rogue wave formation (see also [76]). Smith and Swan [66] also highlighted the importance of nonlinearity and unsteadiness in numerical simulations of extreme focused waves. Sriram et al. [70] considered the effect of linear and second-order generation signals on focused wave evolution in a parametric study within a physical wave flume. Sriram et al. [70] found that spurious sub-harmonic free waves led to additional focus location shifts, and noted that the effect of such waves was likely to be greater for focus locations closer to the wavemaker.

This study seeks to determine the effectiveness of a focused wave group as a predictor of extreme runup on a plane beach (e.g. [37,26]). Instead of representing the incident field as a parameter (such as the significant wave height or period), this approach generates a compact wave group representing an extreme event within the incident wave field (see [41,78,81], for offshore engineering applications) and determines the associated runup. The use of a compact wave group provides information on the physical processes generating extreme runup, and a means for the assessment of the possibility of runup saturation. This concept has been discussed by Raubenheimer and Guza [57], Stockdon et al. [71], Senechal et al. [63], who found that saturation may occur in the frequency band associated with the incident wave spectrum but not in the lower-frequency band associated with infragravity waves. Given that an isolated focused wave group is unlikely to generate free as opposed to bound infragravity waves until breaking occurs, the runup may be expected to saturate for high incident focused wave group amplitudes. This method may provide a complementary approach to existing empirical methods for determining extreme wave runup.

We use the linear NewWave profile of Tromans et al. [78] as the input focused wave group for an experimental/numerical study into extreme wave runup on a plane beach. In NewWave theory a probabilistic analysis shows that the expected local shape of a large wave in a random sea state is the autocorrelation function, i.e. the Fourier Transform of the power density spectrum for the random sea state. NewWave theory was first validated using field data (from wave staff, downward pointing laser and radar rangefinders) from deep water locations where the necessary/underlying assumption that linear frequency dispersion is the dominant process affecting wave transformation is clearly true. NewWave validation at intermediate depth locations has also been demonstrated [73]. Recent analysis of field data from wave buoys by Whittaker et al. [82] has demonstrated that NewWave could represent the average shapes of large storm waves observed in shallow water of depth $kD < 0.5$. This is a powerful result, demonstrating that even in shallow water depths the average shape of the largest event is a property of all the waves in the sea state (i.e. the autocorrelation function).

The target NewWave free surface elevation time series of the focused wave group is given by the linear superposition of wave modes:

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

where σ is the standard deviation of the sea state (with an associated variance $\sigma^2 = \sum S_{\eta\eta}(\omega_i)\Delta\omega$ in this discretised form), $S_{\eta\eta}$ is the power spectral density and ω_i is the angular frequency corresponding to the wavenumber k_i. A Pierson-Moskowitz spectrum with a peak frequency of $f_p = 0.464$ Hz, corresponding to a kD value of 0.71 for the offshore water depth $D = 0.5$ m, is adopted in the experimental/numerical focused wave study reported herein. The focusing event (x_f, t_f) is the spatial and temporal position/instant at which the wave group is in its most compact form according to Eq. (2), which applies the linear dispersion relation for a constant water depth D (allowing calculation of the required paddle signal to generate the focusing event). It is important at this point to clarify the difference between the phase of each Fourier component and the overall shape of the focused wave group. A single frequency component of an irregular sea state would have the form $a_i\cos(k_i x - \omega_i t + \phi_i)$, where ϕ_i is the phase of each wave component randomly chosen from a uniform phase distribution on $(0, 2\pi)$. However, in formulating a focused wave group this phase is not random, and can be expressed in terms of the phase of the entire wave group in the form $\phi_i = -k_i x_f + \omega_i t_f + \phi$, where (x_f, t_f) is the focusing event and ϕ is the phase of the wave group at focus. Hence, the