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Numerical analysis of run-up oscillations under dissipative conditions

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ABSTRACT

This paper presents laboratory and numerical simulations of run-up induced by irregular waves breaking on a gentle-sloping planar beach. The experimental data are well reproduced by a numerical model based on the non-linear shallow water equations. By extending the incoming wave conditions considered in the laboratory experiments, the model is applied to study the run-up variability under highly energetic incoming conditions. The numerical results support the idea that, for cases characterized by the same incident peak frequency, infragravity run-up increases almost linearly with the offshore significant wave height. Moreover, the most energetic conditions lead to an upper limit of the swash similarity parameter of about 1.8.

1. Introduction

Nearshore waves drive oscillations of the shoreward water's edge on the foreshore. The vertical location of the water's edge defines the run-up which results from the sum of a steady and a time-varying component. The steady component is the wave set-up consisting in a superelevation of the mean water level forced by the mean radiation stress gradient within the surf zone (Longuet-Higgins and Stewart, 1964). The time-varying component is represented by swash fluctuations forced by that part of wave energy which is not dissipated by breaking processes eventually resulting in a reflection at the shoreline (Miche, 1951).

A large amount of nearshore sediment transport occurs within the swash zone pointing out the importance of this relatively narrow region in the global coastal evolution. Swash hydrodynamics are of great relevance since they drive the sediment exchanges between the surf zone and the subaerial beach (Masselink and Hughes, 1998; Masselink and Puleo, 2006) potentially leading to dune erosion during adverse sea conditions (Ruessink et al., 2012; Ruggiero et al., 2001). In addition, extreme run-up events can generate beach overwash and structure overtopping.

For monochromatic waves, laboratory data are consistent with the Miche (1951) hypothesis which states that swash saturation is expected when the incident wave amplitude increases above the limiting amplitude for non-breaking standing waves on a slope. Saturation implies that, as a result of dissipation induced by breaking, run-up does not increase with increasing offshore wave height. The onset of swash saturation is expected for a critical value of the non-dimensional parameter ε_s (Miche, 1951). For monochromatic standing waves, Carrier and Greenspan (1958) proposed an analytical solution in which wave breaking occurs when $\varepsilon_s = 1$. Experimental estimates of the critical value for ε_s range from 1.25 to 3 (Baldock and Holmes, 1999; Battjes, 1974; Guza and Bowen, 1976). Due to wave–wave interactions and energy transfer to low-frequency motion as waves approach the shore, swash oscillations forced by irregular waves are significantly different with respect to monochromatic cases. However, the observations of random wave run-up qualitatively confirm the Miche (1951) saturation hypothesis. Field data suggest that run-up is often saturated at sea-swell frequencies (Guza and Thornton, 1982; Holman and Sallenger, 1985) with saturation potentially extending even at infragravity frequencies during highly energetic storms (Ruessink et al., 1998). Ruggiero et al. (2004) and Senechal et al. (2011) collected video measurements of wave run-up under highly dissipative conditions pointing out that saturation is likely to extend to almost the entire infragravity frequency band.

The infragravity band saturation of run-up appears strictly related to low-frequency energy dissipation in the surf zone. Infragravity energy damping inside the surf zone has been investigated in the last decade by means of field, laboratory and numerical approaches. The laboratory observations of Battjes et al. (2004) and van Dongeren et al. (2007) proposed that long wave breaking is the main agent responsible for infragravity wave damping. These findings have been supported by the field observations of de Bakker et al. (2014) who identified infragravity-wave breaking as the dominant dissipation mechanism close to the shoreline. On the other hand, the field work of Thomson et al. (2006) and Henderson et al. (2006) provided evidence of energy transfer from infragravity to incident wave components. Using high spatial resolution numerical data, Ruju et al. (2012) suggested that infragravity energy losses are the result of energy transfer to incident

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wave components in the outer and middle surf zone, whereas long wave breaking prevails in the inner surf zone. The mechanics of these processes have been questioned by Baldock (2012) who discussed the dissipation of long waves released by short wave breaking. Furthermore, the role played by friction has been analysed by Henderson and Bowen (2002).

Several field studies have reported high correlation levels between wave energy in deep waters and low-frequency energy in the inner surf and in the swash zone (Guza and Thornton, 1982; Herbers et al., 1995; Ruessink, 1998). Useful empirical parameterizations have been formulated relating run-up to the incoming wave condition, typically including offshore wave height and peak period, and the beach slope (Holman and Sallenger, 1985; Nielsen and Hanslow, 1991; Stockdon et al., 2006). More recently, Guza and Feddersen (2012) addressed the dependence of run-up on the directional and frequency spread by means of numerical modelling. The mentioned work has improved the understanding of long-wave dynamics and run-up, however some issues such as, for example, the low-frequency energy damping in shallow waters and the run-up saturation on the foreshore are still open. In spite of the increased capability of run-up prediction for a wide range of wave conditions and beaches, lack in the knowledge about the prediction of run-up induced by energetic conditions still remains. Significant uncertainties are related to strongly dissipative conditions when saturation is likely to extend over infragravity frequencies potentially leading to an upper limit of wave run-up as hypothesized by Senechal et al. (2011).

It is the objective of this work to study swash oscillations under highly dissipative conditions by means of laboratory and numerical data. Experimental data on swash oscillations are used to validate the numerical model SWASH on a gently-sloping beach. The dependence of swash oscillations induced by energetic incoming sea states is addressed by means of numerical simulations extending the conditions considered in the laboratory experiments. In particular, the simulated conditions yield the saturation frequency of swash components well below the incident band in order to investigate the run-up behaviour under highly dissipative conditions.

The laboratory experiments are described in Section 2. Section 3 introduces the numerical model and provides the model validation. New numerical simulation extending the range of incoming wave height with respect to the laboratory experiments are described and discussed in Sections 4 and 5, respectively. Section 6 points out some conclusions.

2. Experimental set-up

2.1. Wave flume and instrumentation

The physical experiments included in the GLOBEX project were carried out in the Scheldt flume (The Netherlands). Here, the experimental facilities and the instrumentation relevant for this work are outlined. A more comprehensive description of the laboratory experiments is presented in Ruessink et al. (2013) and other GLOBEX reports mentioned therein.

The Scheldt flume is 110 m long, 1 m wide and 1.2 m high. Waves were generated by a hydraulically-driven piston-type wave maker located at one end of the flume. Glass sidewalls delimit the lateral boundaries of the flume, except in a 7 m region located in the middle of the flume where concrete sidewalls are present. The fixed bottom profile was made of concrete. A horizontal part of 16.57 m extended between the wave maker and the toe of the slope, then a beach characterized by a gentle constant slope β of 1:80 started reaching the end of the flume. The still water depth during the experiments was set at 0.85 m in the constant depth section; the undisturbed shoreline therefore lay at 84.57 m from the mean position of the wave maker (Fig. 1).

Free surface displacements were measured using 10 and 12 resistance (RWG) and capacitance (CWG) wave gauges. A capacitance gauge parallel to the beach slope at a height of 0.8 cm above the bottom detected the run-up oscillations on the beach face. Measured run-up therefore corresponds to the highest position on the beach face where water depth exceeds 0.8 cm.

The target wave maker motion is provided by a second order wave control signal (van Leewen and Klopman, 1996) in order to reproduce bound subharmonic and superharmonic waves suppressing incident free waves generated at the wave maker. Moreover, active reflection compensation was used to absorb outgoing waves and minimize reflection at the wave maker. Wave conditions were irregular but deterministic and therefore reproducible allowing data to be collected at multiple cross-shore locations by means of experiment repetitions. Each experiment was run ten times leading to a final spatial resolution of wave gauges of 0.37 m in the most onshore part of the flume for $x > 54$ m. The most offshore wave gauge, located 7 m shoreward of the wave paddle, was fixed and used as reference control gauge. As a result of the combined ten runs, 190 locations were achieved for wave gauges. The sampling frequency for the wave gauges and run-up wire was 128 Hz providing a high temporal resolution. Each experiment was 4500 s long, in order to achieve a proper value of degrees of freedom for the planned bispectral analysis.

2.2. Wave characteristics

Irregular wave conditions matching a JONSWAP spectrum as well as bichromatic and regular waves were conducted during the laboratory experiments. In this work, only the irregular-wave cases are examined. They are characterized by varying peak frequencies (f_p), significant wave height (H_s) and peak enhancement factor (γ). Cases A1 and A3 represent moderate incoming conditions ($H_s = 0.1$ m), whereas the relatively high H_s of case A2 provides the most energetic conditions ($H_s = 0.2$ m). Case A3 is characterized by a narrow-banded wave spectra ($\gamma = 20$) and a relatively large peak period ($T_p = 1/f_p = 2.25$ s), usually related to clean swells generated by distant storms. Note that, considering the scale factor of 0.05, the significant wave height and peak period

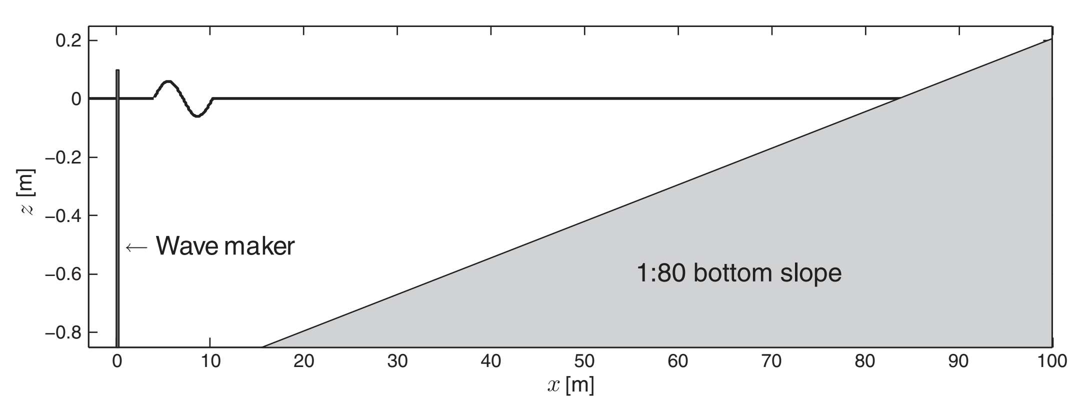

Fig. 1. Cross-shore bottom profile and still water level.