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The influence of swash-based reflection on surf zone hydrodynamics: a wave-by-wave approach

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ABSTRACT

A detailed understanding of the behaviour of waves in the nearshore is essential for coastal engineers as these waves cause beach erosion, coastal flooding and damage to coastal structures. Significantly, the influence of reflected waves is often neglected in surf zone studies, although they are known to influence wave properties and circulation in the nearshore. In this paper, a phase-resolving model is rigorously applied to model conditions from the prototype-scale BARDEXII experiment in order to examine and assess the influence of swash-based reflection on surf zone hydrodynamics at both the individual wave and time-averaged timescales. Surface elevation is separated into incoming and outgoing signals using the Radon Transform and a crest tracking algorithm is used to extract incident and reflected wave properties. It is found that on steep beaches ($\tan\beta > 1{:}\,9$) the swash-based reflection - the reflection generated in the swash during the backwash - contributes significantly to the intrawave variability of individual wave properties such as the wave height to water depth ratio γ, through the generation of quasi-nodes/antinodes system. For γ expressed with individual wave heights, variations up to 25% and 40% are obtained for the modelled regular and irregular wave tests, whereas it reaches 15% when it is based on the significant wave height. The outgoing wave field-induced hydrodynamics is also found to affect time-averaged parameters: undertow and horizontal velocity skewness. The undertow is mainly strengthened, particularly in the shoaling region where the outgoing component dominates over the contribution from the incoming wave field. Offshore of the bar, an onshore-directed flow streaming close to the bed is also generated under the outgoing wave field, and is suspected to help in stabilising the bar position. This, along with the influence of the outgoing wave field on the horizontal velocity skewness and the presence of quasi-standing waves, suggests a complex contribution of the hydrodynamics induced by swash-based reflection into sediment transport rates and nearshore bar generation/migration.

1. Introduction

Wave reflection from beaches and other coastal features is known to influence incident wave-induced hydrodynamics and therefore morphodynamics [12].

While there are many studies of structure-induced reflection present in the literature (see Zanuttigh and van der Meer [3], for a relatively recent comparison of extensive datasets), it is evident that prior studies focusing on wave reflection from natural beaches, especially in the sea/swell band ($0.05\ \mathrm{Hz} \le f \le 0.5\ \mathrm{Hz}$), are relatively limited. The reflection of monochromatic waves over a slope was first investigated by Iribarren and Nogales [4], and Miche [5] and it has been shown that the reflection coefficient of a slope, defined as the ratio between incident and reflected wave height $K = H_r/H_i$, is linked to the surf-similarity parameter [6]:

$$\xi = \tan\beta/\sqrt{H_o/L_o} \tag{1}$$

where β is the structure or beach slope, and H_o and L_o are the offshore wave height and wavelength, respectively. While the reflected wave phase was found to be only dependent on the offshore wave steepness and the slope [7], the amplitude of reflected waves are substantially influenced by the bottom roughness and permeability, but also the nature of wave transformation across the surf zone (Battjes [6], Hughes and Fowler [7], Miles and Russell [8] and many others). By presenting cross-shore varying reflection coefficients from two field-based experimental datasets, Baquerizo et al. [9] observed a net increase in reflection coefficients shoreward of the break point, and suggested that when defining the reflection coefficient of a beach, it should be

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measured as far offshore as possible. Although this approach is appropriate for studying the bulk outgoing wave energy from a beach, it presents several issues. Assessing the outgoing energy further from shore increases the risk of observing additional phenomenon, particularly from non-linear wave interactions [10,11], that can lead to reflection coefficients higher than unity [12]. Furthermore and as discussed by Battjes [6], based on the methodology of Miche [5], the processes responsible for incident wave energy dissipation in the surf zone (mainly friction and breaking) have to be approximated, while a measurement close to the swash zone would lead to an exact estimation of reflected waves (height and phase), using the local incident properties.

In the few field-based studies focusing on wave reflection in the sea/swell range of frequencies, it was generally demonstrated that reflection could be substantial [13,8,14]. Using an array of 24 bottom-mounted pressure sensors, Elgar et al. [13] found that up to 18% of the incident sea-swell frequency band was reflected back into the surf zone. These relatively high levels of reflected energy in the surf affect the incident waves in a variety of ways. Fluctuations in the currents velocities due to the reflected wave orbital velocities influence the sediment suspension [1], also potentially influencing the velocity skewness, important for onshore sediment transport [15,16]. Instantaneous sea levels are also influenced by the presence of seaward propagating wave crests and troughs, which influence the wave height to depth ratio γ, due to the presence of quasi-standing waves [17]. Many parameterisations are present in the literature to describe the cross-shore variation of this wave parameter, related to the wave energy dissipation (see for example the pioneering work of Battjes and Janssen [18]). While existing parameterisations of γ do not explicitly account for wave reflection, both γ and reflection are a function of beach slope and wave number [19,20,21]. It is known that the beach slope controls the wave reflection to a great extent (see above, and Almar et al. [14,22]). Through observation of the influence of strong backwash flows on the generation of individual reflected waves at the surf-swash boundary, a link might be expected between reflected waves generated by swash flows and the wave height to water depth ratio of individual waves in the surf zone, though no evidence is present in the literature.

A lack of field-based studies of sea/swell reflection on beaches can be explained by the complexity in measuring the energy bulk reflected from a beachface. Several methods to separate incoming from outgoing wave fields exist; see for example Inch et al. [23] for a recent description. Correlation functions between 2 wave gauges were used (Kajima [24], Thornton and Calhoun [25] in Goda and Suzuki [26]) before Goda and Suzuki [26] introduced the use of Fast-Fourier Transform (FFT) to speed up this process. This was later extended to a larger array of wave gauges - see for example Mansard and Funke [27], Zelt and Skjelbreia [28] or Lin and Huang [29] - which enables the error in the separation process to be reduced [23]. Other methods such as PUV (Pressure, U horizontal and V vertical current velocities, Guza and Bowen [30]), or approaches based on long-wave theory described in Guza et al. [31] use collocated pressure or surface elevation signals, and horizontal current velocities to separate incoming and outgoing signals at a cross-shore location. Using a totally different approach, Almar et al. [32] describe the use of the Radon Transform (RT) for nearshore wave studies, with the objective of finding tools to facilitate wave-by-wave analyses. Mostly used in image processing, the RT can be applied to the projection of a cross-shore/temporal diagram $\eta(x, t)$ into points in the Radon (polar) space. This method is therefore particularly suitable in the surf zone as with increasing non-linearities, the wave tracks appear as well-defined lines in such diagrams (e.g. Almar et al. [33]). Almar et al. [32] successfully separated incident and reflected long-wave signals from a laboratory dataset and demonstrated that the results compared well with those from a Boussinesq model.

In this study, the RT is applied to the results from a phase-resolving numerical model simulating two monochromatic and one irregular wave tests, performed at prototype-scale in the Delta flume during the BARDEXII project [34]. The primary objective is to study the impact of reflected waves on incident wave properties and surf hydrodynamics with a focus on sea/swell waves. For irregular waves, the free surface is actually a sum of wave trains, with different frequency and possibly direction (incident and reflected). In this regard, a wave-by-wave approach is developed based on the previous work of Martins et al. [21], allowing individual wave tracking from the shoaling area to the runup limit, and back into the flume after reflection.

The paper is organised as follows. Section 2 introduces the experimental and numerical datasets. The numerical model is validated using a large array of instruments, including a Terrestrial Laser Scanner (TLS) that enables the description of the wave shape during breaking. The signal separation in incoming/outgoing components and the wave-by-wave approach used to track individual wave properties are described in Section 3. Section 4 presents the results on the separation methods and its application for the study of swash-based reflection influence on surf zone hydrodynamics at the individual wave timescale. The concept of swash-based reflection is notably explained through a link with swash events potential energy. The results and the influence of reflection at longer timescales are then discussed in Section 5. Finally Section 6 provides the conclusions of this study.

2. Experimental and numerical datasets

2.1. The BARDEXII experiments

The present study uses experimental data obtained during the 2-month-long BARDEXII experiment [34]. In order to study wave processes and cross-shore sediment transport in the surf and swash zones, a coarse sandy beach/barrier system was built in the prototype-scale Delta Flume (Vollenhove, The Netherlands). The A6 and A7 monochromatic test cases (hereafter A6-mono and A7-mono) and A6-01 irregular wave test are the focus of the present study [34]. Regular second-order Stokes waves were generated during the A6-mono and A7-mono tests by a second-order wave steering system at x=0 m, with an Active Reflection Compensation system (ARC) for the absorption of reflected waves. For the A6-01 irregular test, a JONSWAP spectrum with a peak enhancement factor of 3.3, was imposed in the wave flume. The initial beach profile of 1:15 slope between $x = 49 - 109$ m evolved under the wave action during Series A1 to A7 to result in the bed profiles presented in Fig. 1, presenting a much steeper upper beach face, a bar system for the A6-01 and A6-mono, and a terrace for the A7-mono. The wave forcing conditions and beach slope for the different wave tests examined here are presented in Table 1.

A large array of instrumentation was used during the experiments, and only part of the experimental dataset is used to validate the numerical model used herein. The positions of the instruments used in the present work are shown in Fig. 1. A series of pressure transducers (PT) and electro-magnetic current meters (EMCM) both sampled at 20 Hz were located in the shoaling and surf zones to measure the pressure and flow velocity under propagating and breaking waves. Two terrestrial laser scanners were deployed to measure free surface elevations within the flume, the first was positioned in the surf zone at x=73.6 m, 3.9 m above mean sea level (MSL) while the second was deployed at x=88.3 m, 3.8 m above MSL to study the swash zone hydrodynamics and morphodynamics. The TLS recorded data at an angular resolution of 0.25° and sample rate of 35 Hz; the measurements were processed following Martins et al. [21] including the correction of the scanner orientation, noise filtering and spatial interpolation onto a regular grid.

TLS data is ideal for wave-by-wave analysis of surf zone processes as the high-spatial and temporal resolutions of the measurements allow for the description of wave geometry and the tracking of individual wave properties through hundreds of cross-shore positions. Physical