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Suspended sediment transport around a large-scale laboratory breaker bar

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ABSTRACT

This paper presents novel insights into suspended sediment concentrations and fluxes under a large-scale laboratory plunging wave. Measurements of sediment concentrations and velocities were taken at 12 locations around an evolving breaker bar, covering the complete breaking region from shoaling to inner surf zone, with particular high resolution near the bed using an Acoustic Concentration and Velocity Profiler. Wave breaking evidently affects sediment pick-up rates, which increase by an order of magnitude from shoaling to breaking zone. Time-averaged reference concentrations correlate poorly with periodic and time-averaged near-bed velocities, but correlate significantly with near-bed time-averaged turbulent kinetic energy. The net depth-integrated suspended transport is offshore-directed and primarily attributed to current-related fluxes (undertow) at outer-flow elevations (i.e. above the wave bottom boundary layer). The wave-related suspended transport is onshore-directed and is generally confined to the wave bottom boundary layer. Cross-shore gradients of sediment fluxes are quantified to explain spatial patterns of sediment pick-up and deposition and of cross-shore sediment advection. Suspended particles travel back and forth between the breaking and shoaling zones following the orbital motion, leading to local intra-wave concentration changes. At locations between the breaker bar crest and bar trough, intra-wave concentration changes are due to a combination of horizontal advection and of vertical exchange with the bedload layer: sediment is entrained in the bar trough during the wave trough phase, almost instantly advected offshore, and deposited near the bar crest during the wave crest phase. Finally, these results are used to suggest improvements for suspended sediment transport models.

1. Introduction

Over the last decades, experimental and numerical studies have significantly advanced the understanding of sediment transport processes and the ability to predict suspended and bedload transport rates for non-breaking waves [65]. However, in the breaking region, existing formulations for suspended sediment concentrations and transport may not be valid due to effects of breaking-generated turbulence and of cross-shore hydrodynamic non-uniformity (i.e. cross-shore changes in wave shape and undertow) which are not fully understood [65].

Laboratory [43,52,67] and field studies [31,6,70] have reported large amounts of suspended sediment in the breaking zone, related to the enhancing effects of breaking-generated vortices on sediment entrainment from the bed [1,28,31,48,53,67] and on vertical sediment mixing [2,31,35,68]. These processes depend on the characteristics of the breaking wave, with plunging breakers being more effective in entraining and mixing sediment than spilling breakers [2,31]. This relates to differences in turbulence behavior, with higher production rates and a more rapid downward spreading of breaking-induced turbulence found under plunging than under spilling waves [58].

Due to the dominance of breaking-induced vortices on sediment pick-up, existing formulations for near-bed reference concentrations that are based on orbital and time-averaged velocities [32,64] may not apply in the wave breaking region [2]. Instead, formulations that are based on breaking-induced turbulence and that take the breaker type into account (e.g. [27,52,24]) appear more appropriate. An additional complication is that due to strong horizontal sediment advection in the breaking region [48,69] the near-bed concentrations may not always be related to local hydrodynamics only.

The net horizontal suspended flux in the breaking region is the result of two opposing fluxes with similar magnitudes: an offshore-directed current-related flux and an onshore-directed wave-related flux [34,37,46,57]. The former is driven by the undertow, whereas the latter relates to the wave asymmetry [17,19]. Time-varying breaking-generated turbulence, with higher intensities during the crest half-cycle, has been suggested as an additional factor contributing to onshore wave-

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related suspended sediment fluxes [58,7]. Yoon and Cox [69] presented experimental evidence for increased onshore wave-related suspension fluxes due to intermittent suspension events that occur preferentially during the wave crest phase following events of high turbulent energy. However, Scott et al. [48] found, by combining data from the same experiment with numerical simulations, that suspension events occur mainly during the wave trough phase and contribute to offshore-directed fluxes. The individual effects by turbulence and wave asymmetry on sediment fluxes are difficult to assess because the two parameters correlate positively in the breaking region [67,1].

Although previous research highlighted clear effects of wave breaking on sediment suspension and fluxes, there are still open research questions. Most of the aforementioned studies are based on local point measurements of sediment concentrations at few elevations in the water column, sometimes combined with co-located velocity measurements to estimate the local sediment fluxes. These measurements did not capture the complete vertical distribution of fluxes since the near-bed region including the wave bottom boundary layer (WBL), where large contributions to total suspended transport can be expected, was not accurately resolved. Such measurements of WBL flow and time-varying near-bed turbulence are also essential in relating the observed sediment processes to hydrodynamic forcing. In addition, most of the previous experimental studies covered only a few cross-shore locations in the shoaling and breaking region. This strongly limits the study of cross-shore advection of suspended sediment and the effects of cross-shore non-uniformity in hydrodynamics (i.e. flow and turbulence) on suspended sediment processes.

Here we present new high-resolution measurements of suspended sediment transport processes under a plunging wave in a large-scale wave flume. Measurements were obtained at 12 cross-shore locations along a sandy breaker bar, covering the complete breaking region from shoaling zone to inner surf zone. Sediment concentration and velocity measurements cover most of the water column, with particular high resolution of time-varying concentrations and sediment fluxes in the near-bed region (including the WBL). The aim is to improve insights into suspended sediment processes in the breaking region, with particular focus on the current-related, wave-related and turbulent suspended sediment flux components and their contributions to the total net suspended transport. These fluxes are also used to explain the intra-wave near-bed concentration field in terms of horizontal sediment advection and vertical exchange of sediment between the suspension and bedload layer (pick-up and deposition). Results of the sediment dynamics are related to the detailed near-bed flow and turbulence measurements obtained from the same experiment and reported in van der Zanden et al. [62].

The paper is organized as follows: the experiment is described in Section 2. Section 3 presents the bed profile evolution and the cross-shore variation in the main hydrodynamic parameters. Section 4 presents results on suspended sediment concentrations (4.1), fluxes and net transport rates (4.2) and horizontal advection and pick-up/deposition (4.3). The results are used to discuss potential improvements to suspended sediment transport formulations, which are incorporated in numerical morphodynamic models used for engineering purpose, for breaking-wave conditions (Section 5).

2. Experimental description

2.1. Facility and test conditions

The experiments were carried out in the large-scale CIEM wave flume at the Universitat Politècnica de Catalunya (UPC) in Barcelona and have been described before in detail by van der Zanden et al. [62]. Fig. 1 shows the experimental set-up and bed profile. Cross-shore coordinate x is defined positively towards the beach, with $x = 0$ at the toe of the wave paddle. Vertical coordinate z is defined positively upwards with $z = 0$ at the still water level (SWL); ζ is the vertical coordinate positive upwards from the local bed level. The initial bed profile consisted of a bar-trough configuration that was deliberately separated from the shoreline so that the transport dynamics around the bar would not likely be affected by processes in the swash zone. The test section can be roughly divided into an offshore-facing bar slope (x = 35.0 to 54.8 m; steepness $\tan(\alpha)$ = 1:10), followed by a steeper shoreward-facing bar slope (x = 54.8 to 57.5 m; $-\tan(\alpha)$ = 1:4.7), and a mildly sloping bed shoreward from the bar trough (x = 57.5 to 68.0 m; $\tan(\alpha)$ = 1:95). The test section consisted of medium sand (median diameter D_{50} = 0.24 mm; D_{10} = 0.15 mm; D_{90} = 0.37 mm) with a measured settling velocity w_s = 0.034 m/s. The grain size standard deviation σ_g = 1.4, quantified through the geometric method of moments, classifying the sediment as 'well sorted' [8]. The profile shoreward of the mobile test section (x > 68.0 m) followed a 1:7.5

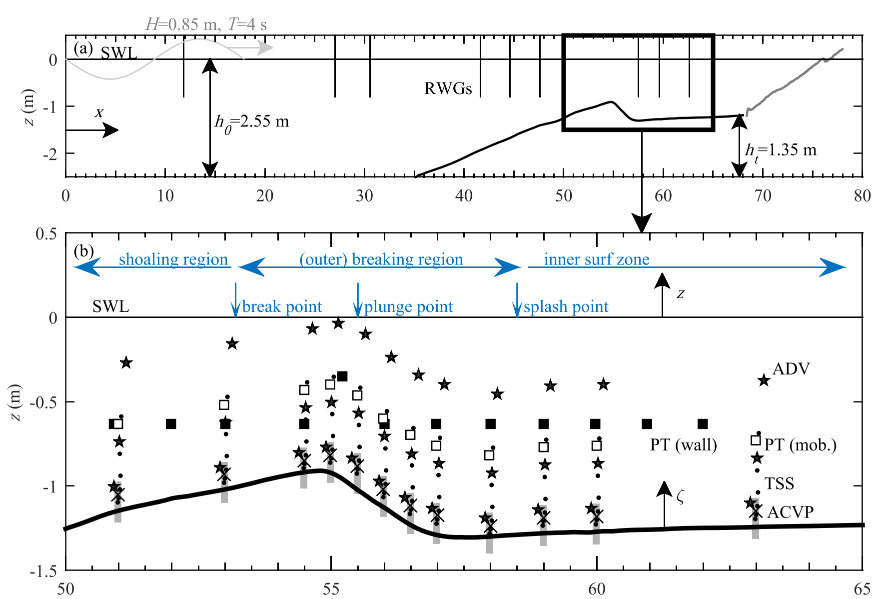

Fig. 1. Experimental set-up and measurement locations. (a) Initial bed profile (black line) and fixed beach (grey line), and locations of resistive wave gauges (RWGs, vertical black lines); (b) Measurement positions of ADVs (star symbols), mobile-frame Pressure Transducers (PT, white squares), wall-deployed PTs (black squares), Transverse Suction System nozzles (TSS, black dots), Optical Backscatter Sensor (black crosses), and measuring range of mobile-frame ACVP (grey boxes).