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Wave groups and sediment resuspension processes over evolving sandy bedforms

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High resolution measurements of the water velocity, bedforms and suspended sediment concentration were made using an Acoustic Doppler Velocimeter, acoustic bedform scanners and an Acoustic Backscatter System, under irregular free-surface waves. The waves were generated in a large scale flume facility above a number of bedform types. These data were analysed in (i) the frequency domain in order to examine the frequency at which sediment suspensions occurred in the oscillatory bottom boundary layer and the free stream; and (ii) the time domain in order to examine the instantaneous entrainment and vertical transport of sediment at intra-wave, wave average and wave group time scales. During the course of the experiments the significant wave height was systematically incremented enabling the character of sediment suspensions to be studied under a number of flow and bedform regimes. Wave groups were identified as an important control over sediment suspensions in both the wave boundary layer and free stream, with fluctuations in the suspended sediment concentration occurring at low, wave group, frequencies. However, the initial entrainment process, within the wave boundary layer, occurred at intra-wave frequencies. In contrast, in the free stream, sediment suspensions were dominated by the vertical transport of sediment at wave group time scales. During wave groups the sediment suspension field was characterised by the upward transport of sediment due to the continual injection of turbulence under a series of waves which generated a wave pumping effect. The character of a wave group is considered to be an important control over sediment suspensions in the free stream. Four distinct types of wave group were identified and the instantaneous sediment suspension field below each type examined. Such comparisons were possible using the high resolution Acoustic Backscatter System which enabled both intra-wave and wave group processes to be resolved up to 0.8 m above the bed.

1. Introduction

Under irregular waves, the suspended sediment concentration (SSC) changes over a range of time scales (Hanes, 1991; Osborne and Greenwood, 1993; Hay and Bowen, 1994b; Williams et al., 2002). These fluctuations occur at high, intra-wave, frequencies associated with individual waves (Osborne and Vincent, 1996; Villard and Osborne, 2002; O'Hara Murray et al., 2011) and also at low, infra-gravity, frequencies (Hanes, 1991; Osborne and Greenwood, 1993) associated with wave groups (Clarke et al., 1982; Larsen, 1982; Vincent et al., 1982, 1991; Shi and Larsen, 1984; Hay and Bowen, 1994a). The suspension of sediment is strongly dependent on the hydrodynamics and the type of bedforms present (Vincent et al., 1991; Ribberink and Al-Salem, 1994; Vincent et al., 1999; Grasmeijer and Kleinhans, 2004). Above steep-sided two-dimensional ripples, flow separation can occur during each wave half-cycle, forming a sediment-laden vortex, which at flow reversal is ejected out of the wave boundary layer (WBL) and into the free stream (Nakato et al., 1977; Hansen et al., 1994; Sleath and Wallbridge, 2002). In these conditions, the intra-wave suspension of sediment is a convective entrainment process occurring twice in a wave cycle (Davies and Thorne, 2005; Van der Werf et al., 2007; Thorne et al., 2009). When the bed is plane the entrainment of sediment occurs when the peaks in the bed shear stress generate turbulence, which occurs just ahead of peak free stream velocity (Davies and Thorne, 2008), and is a diffusive process. These intra-wave entrainment processes are strongly dependent on the properties of each incident wave—its height, period and asymmetry. During the passage of a group of waves, however, the SSC also depends on the properties of antecedent waves. For example, at a given height above the bed the SSC is often higher under waves later in a group than under similar waves early in a wave group (Hanes, 1991; Villard et al., 2000; Vincent and Hanes, 2002). This can be due to the process of wave pumping, where within each wave cycle sediment is entrained to increasingly higher elevations before it can

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settle. The continual injection of turbulence under consecutive waves in a wave group leads to more sediment being supported, and to the vertical advection of turbulence during the passage of a wave group (Osborne and Greenwood, 1993). A consequence of the wave pumping process is a time lag between the initial entrainment of sediment at the bed and higher than average concentrations at high elevations in the free stream (Vincent and Hanes, 2002).

This work uses high frequency acoustic technology to examine time series of SSC up to 0.8 m above a number of different bedform types that developed in a large scale wave flume as the significant wave height was systematically incremented. In addition to the SSC, the water velocities and the bedform dimensions and geometries were measured using acoustics. Over a variety of bedforms, the fluctuations in SSC within the WBL are considered to be associated with intra-wave entrainment processes, while in the free stream the SSC variation is deemed to be a function of the wave group and is dependent on antecedent waves. This is because the vertical extent to which the intra-wave processes dominate is often limited by the ripple height (Van Rijn, 1993; Van der Werf et al., 2006; Thorne et al., 2009), whereas the process of wave pumping can entrain sediment high into the free stream. This work aims to examine the temporal differences between sediment resuspension in the WBL and free stream under wave groups. Wave groups are characteristic of irregular free surface waves typical of field conditions. The importance of considering wave groups when trying to understand sediment entrainment and transport processes is highlighted, and raises the question of how important the character of the wave group is, such as the number of waves and distribution of wave heights in a group. Finally, a number of future research avenues and experimental refinements are suggested.

2. Experiments, instrumentation and data analysis

The Deltaflume of Deltares Delft Hydraulics, the Netherlands, is a large scale flume (240 m long, 5 m wide and 7 m deep) that enables sediment transport processes to be monitored at field scale. Irregular waves with a JONSWAP spectrum (Carter, 1982) were generated for a series of significant wave heights during which the bed adopted a number of different morphological forms. A series of experiments was conducted over an upper-medium-grained sand bed in water depths of approximately 4 m. The 11 experiments are here referred to as M01–M11. Twelve samples of the bed sediments were taken from a variety of locations on the bed and their volume size distributions were determined using a Coulter Laser Granulometer. The bed sediments were found to have a lognormal grain size distribution with a median grain diameter, D_{50}, of 375 ± 30 μm. The bed was 0.7 m deep and was laid down in the centre of the flume in a 30 m long region spanning the width of the flume. Prior to the 25 min measurement burst of each experiment, the irregular waves were run for one hour to allow the bedforms to reach equilibrium (Marsh et al., 1999) and for any air trapped in the bed sediments to degas. Fig. 1 is a schematic of the instruments deployed on a frame mid-way along the sandy bed and at one side of the Deltaflume. The Nortek Vector Acoustic Doppler Velocimeter (ADV) measured the water velocities at one point ~0.5 m above the bed and recorded the three components of flow at 16 Hz. The cross-shore cross-sectional and plan-form geometry of the bedforms were monitored by a 2.0 MHz Acoustic Ripple Profiler (ARP) and 1.2 MHz Sector Scanning Sonar (SSS), respectively. Vertical profiles of the suspended sediment concentration, at 4 Hz intra-wave time scales, were measured by an Acoustic Backscatter System (ABS). The ABS comprised three transceivers operating at 1.0, 2.0 and 4.0 MHz, aligned along-shore and perpendicular to the oscillatory flow. Finally, pumped samples of the suspended sediments (Bosman et al., 1987) were taken from up to five heights above the bed during M03–M11. These samples were analysed using laser granulometry to obtain grain size distributions of the suspended sediment.

In the experimental study, measurements of the wave forcing, bedforms and suspended sediment concentration were made. Wave generated bedforms quickly emerged, and, as the significant wave height was incremented, exhibited a number of different plan-form and cross-sectional configurations. Thus, measurements of the SSC were made above an evolving sandy bed and the response of the SSC during the passage of wave groups, and over different bedforms, was examined.

2.1. Irregular wave forcing and wave groups

For each experiment, the ADV velocity components were despiked using a Phase-Space Thresholding Method (Goring and Nikora, 2002) and rotated to correct for any misalignment of the instruments with the main flow direction by calculating the principle axis of variation (Emery and Thompson, 1997). During

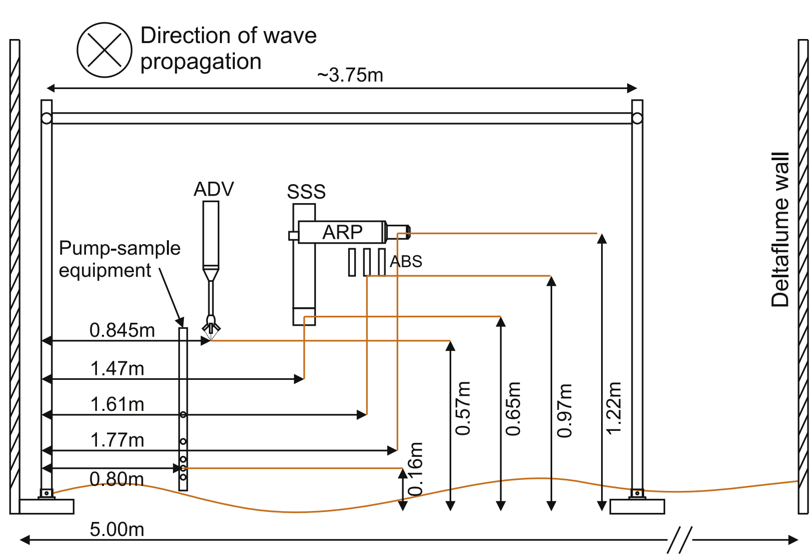

Fig. 1. A schematic of the instruments deployed on a frame in the Deltaflume showing the locations of the Acoustic Doppler Velocimeter (ADV), Acoustic Ripple Profiler (ARP), Sector Scanning Sonar (SSS), Acoustic Backscatter System (ABS) and pump sampling equipment.