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Measurements of suspended sediment transport and turbulent coherent structures induced by breaking waves using two-phase volumetric three-component velocimetry

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A B S T R A C T

Sediment suspension and transport under plunging regular waves was investigated in a laboratory surf zone using the volumetric three-component velocimetry technique. The two-phase flow measurements captured the motions of sediment particles simultaneously with the three-component, three-dimensional velocity fields of turbulent coherent structures (large eddies) induced by plunging breakers. Sediment particles were separated from fluid tracers based on a combination of particle spot size and brightness in the two-phase flow images. The interactions between the large eddies and bottom sediment were investigated in the outer surf zone. The measured data showed that breaker vortices impinging on the bottom was the primary mechanism that lifted sediment particles into suspension. High suspended sediment concentrations were found in the wall-jet region where the impinging flow was deflected outward and upward. Sediment particles were also trapped by counter-rotating vortices behind the down flow. Suspended sediment concentrations were significantly lower in the impingement zone where the fluid velocities were downward, even though the turbulent kinetic energy in the down flow was very high. Suspended sediment concentration was well correlated with vertical velocity and apparent shear stresses in the deflected flow, and with vorticity magnitude in the counter-rotating vortices. A linear relationship was found between net sediment flux and net turbulent kinetic energy flux over one wave cycle. It was found that a strong deflected flow in front of the impingement zone enhanced onshore sediment transport compared to a more symmetrical flow pattern, while counter-rotating vortices kept sediment particles in suspension for transport offshore after flow reversal. Onshore sediment transport was observed in less than 20% of the breaking waves. In most wave cycles, net sediment flux was directed offshore due to advection by predominantly offshore flow velocities.

1. Introduction

Breaking waves play an important role in sediment transport in the nearshore and beach transformation. Beach and Sternberg [3] reported in a field study that plunging waves can account for more than 50% of the suspended load present in the surf zone. From field data collected on three different beaches under a variety of wave conditions, Voulgaris and Collins [48] found that both reference concentration and vertical distribution of suspended sediment concentration are highly correlated with the local breaker parameter defined by Galvin [12]. In the laboratory, the distributions of suspended sand under spilling and plunging regular waves have been investigated by Sato et al. [32], among others. Their measurements were used by Hsu and Liu [18] and Suzuki et al. [38] to test numerical models of sediment suspension by breaking waves.

To date, modeling sediment transport induced by breaking waves remains a formidable challenge. Nadaoka et al. [27] observed that the wave breaking process generates obliquely descending eddies, which can lift considerable amounts of sand into suspension when they hit the bed. Using a two-camera video system, Zhang and Sunamura [50] described the formation of sand bars due to breaker vortices in a wave flume. A working model of sediment transport induced by breaking waves inherently requires knowledge of the structure of these large eddies and their role in sediment pickup and distribution.

In a pioneering study, Dean [8] showed that the type of beach profiles can be predicted by two parameters: the deep-water wave steepness and ratio of sediment fall velocity to wave period. His heuristic model is based on consideration of whether a sediment particle suspended by breaking-wave-induced vortices is acted upon predominantly by an onshore or offshore fluid velocity field as it falls to

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the bed. He hypothesized that sediment motion would be under the influence of predominantly onshore flow velocities if the fall requires only a short time, but would be dominated by the undertow and is offshore if the fall is long compared to the wave period. Using laser Doppler anemometer (LDA) measurements obtained on a plane slope, Ting and Kirby [42] showed that turbulent kinetic energy is transported seaward under the wave trough level in spilling waves but shoreward in plunging waves, the predominant wave conditions normally associated with erosional and accretive beach profiles, respectively. Their study lent support to Dean's model and demonstrated that there are fundamental differences in the structure of turbulence in spilling and plunging waves.

Recent studies have provided new insights into the process of sediment suspension and transport in breaking waves. Using a stack of acoustic Doppler velocimeters (ADVs) and fiber-optic backscatter sensors (FOBs), Scott et al. [33] conducted co-located measurements of fluid velocities and sediment concentrations over a sandy beach in a large wave flume during the CROSSTEX project. They applied wavelet transform on the measured data and studied the simultaneous occurrence of steep waves, high velocity turbulence events, and high sediment concentration events. They found that the percentage of steep waves associated with high velocity turbulence events and high sediment concentration events is only a small fraction of the total number of steep waves. The percentage of high sediment concentration events caused by steep waves and high velocity turbulence events is also a small fraction of the total number of high sediment concentration events. Their results suggest that breaking-wave-generated turbulence approaches the bed intermittently causing intermittent sediment suspension, and that a large portion of the sediment transport under breaking waves is due to advection from non-local sources. Scott et al. [33] also conducted numerical simulations using a two-phase flow model driven by measured near-bed wave-current and turbulence information. Their model predicted that breaking-wave-generated turbulence would enhance offshore sand transport under erosive wave condition. However, the model was unable to predict the observed beach accretion under accretive condition, which they attributed to other onshore transport mechanisms not considered by the model.

Aagaard and Hughes [1] conducted field measurements of fluid velocities and suspended sediment concentrations. They estimated the bed shear stress from vertical flux of horizontal fluid momentum measured at a small distance above the bed. They found that the instantaneous bed shear stress under plunging breakers is one order of magnitude larger than in surf bores and several orders of magnitude larger compared with shoaling waves. In the plunging breaker case, they found that the peak in sediment concentration coincides with the onshore velocity maximum. The cross-shore sediment flux becomes very large under the wave crest and is onshore-directed resulting in net onshore transport over one wave cycle. They used a fixed vertical velocity threshold to separate the measured instantaneous vertical sediment flux into a component from local breaker vortices and a second component attributed to small-scale turbulence from bed friction or sediment advection from non-local sources. They found that the vertical sediment flux due to local breaker vortices is well correlated with the vertical velocity variance.

Yoon and Cox [49] analyzed additional data collected on a barred beach in the CROSSTEX project. They studied the intermittency in sediment suspension and turbulence near the bed over the bar crest, the bar trough, and in the inner surf zone for both erosive and accretive wave conditions. They defined an intermittent event as when the measured value of turbulent kinetic energy or sediment concentration exceeds a chosen threshold. They found that many of the turbulent events do not cause local suspension of sediments. They concluded that much of the turbulent motion acts to dissipate wave energy rather than suspend sediments. They also found that sediment suspension events uncorrelated with turbulence were mostly associated with strong low-frequency motions, suggesting that advection plays an important role in sediment transport in the surf zone.

More recently, Aagaard and Jensen [2] conducted field measurements of near-bed sediment concentration and sediment diffusivity in the breaker zone and in the inner surf zone on three natural beaches. They found that measured profiles of sediment concentration versus elevation above the bed are concave upward on a log-linear plot for spilling surf bores, and that sediment diffusivity increases approximately linearly with distance from the bed. However, sediment concentration profiles are linear on a log-linear plot for plunging waves consistent with vertically constant sediment diffusivity. Their results indicate that sediment suspension from the bed in spilling waves may be considered as a diffusion process, while vertical mixing by large breaker vortices is mainly a convective process. They also found that plunging breakers are more efficient in transporting sediment landward than spilling breakers.

Since the 1990s particle image velocimetry (PIV) has become a standard technique for measuring instantaneous full-field velocities in a two-dimensional (2D) plane. PIV has been employed in the laboratory by many researchers to measure the velocity field of breaking waves. Some of the more detailed studies include Govender et al. [13,14], Cowen et al. [6], Kimmoun and Branger [24], Huang et al. [19, 20, 21], Sou et al. [35], Ting [39,40,41], and Ting and Nelson [43]. PIV measurements showed that breaking-wave-induced vortices are turbulent coherent structures, which occur sporadically and maintain a distinct phase relationship between the flow variables of their constituent components as they evolve in space and time [4]. Therefore, it is very difficult to understand their interactions with a sediment bed using single-point measurements alone; additional assumptions are required. Ideally, one would need to measure the motions of sediment particles simultaneously with the fluid velocities over the spatial extent of the large eddies in order to fully understand the interactions between the two phases. Recently, Ting and Reimnitz [44] measured all three components of water particle velocities in a three-dimensional (3D) measurement volume under plunging regular waves using the volumetric three-component velocimetry (V3V) technique. They used the three-component, three-dimensional (3C3D) velocity measurements to elucidate the 3D structure of breaker vortices and their evolution with time. Using the V3V technique, it is feasible to measure sediment particle positions and velocities simultaneously with the 3D flow field to answer fundamental questions about sediment pickup and distribution in breaking waves.

In this study, we created a sediment-laden fluid by mixing glass spheres in a wave flume. After the glass spheres had settled, wave breaking was induced on a plane slope and the distributions of solids and fluid tracers in the turbulent flow field were captured simultaneously using a V3V system. The solid and liquid phases were separated based on a combination of particle spot size and brightness in the two-phase flow images. The two-phase flow measurements were used to study the 3D velocity field created when breaker vortices impinged on the bottom, the suspension of sediment particles from the bed, and transport of suspended sediment by organized wave-induced flow (mean flow) and turbulence. The measured data were also used to study the relationships between suspended sediment concentration and the individual flow parameters, and the relationship between suspended sediment flux and turbulent kinetic energy flux.

The remainder of this paper is organized as follows: experimental methods including the principle of operation of V3V and its application to 3C3D velocity measurements in two-phase (solid-liquid) flows are described in Section 2. The measured data and results of data analysis are presented in Section 3, and further discussed in relation to published work in Section 4. Conclusions are drawn in Section 5.