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

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Abstract

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-

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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.

Keywords: Breaking waves; turbulent coherent structures; sediment suspension; sediment transport; two-phase flows; volumetric three-component velocimetry

1. Introduction

Breaking waves play an important role in sediment transport in the nearshore and beach transformation. Beach and Sternberg (1996) 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 (2000) found that both reference concentration and vertical distribution of suspended sediment concentration are highly correlated with the local breaker parameter defined by Galvin (1972). In the laboratory, the distributions of suspended sand under spilling and plunging regular waves have been investigated by Sato et al. (1990), among others. Their measurements were used by Hsu and Liu (2004) and Suzuki et al. (2007) 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. (1988) 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 (1994) 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 (1973) 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 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 (1994) 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 (ADV) and fiber-optic backscatter sensors (FOBs), Scott et al. (2009) 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. (2009) 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 (2010) 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 (2012) 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 (2013) 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. (2002, 2004), Cowen et al. (2003), Kimmoun and Branger (2007), Huang et al. (2009, 2010a,b), Sou et al. (2010), Ting (2006, 2008, 2013), and Ting and Nelson (2011). 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 (Blackwelder, 1988). 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 (2015) 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 3D 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.

2. Experimental Method

2.1. Experimental setup

The experiment was conducted in a 25-m-long, 0.9-m-wide, and 0.75-m-deep tilting flume equipped with a programmable piston type wave generator. Cnoidal waves with wave height of 0.115 m and wave period of 4.0 s were generated in still water depth of 0.298 m. The value of the surf similarity parameter, $s/\sqrt{H_0/L_0}$, where s is beach slope and H_0/L_0 is wave-height-to-wave-length ratio in deep water, is 0.43. The incident wave condition is identical to

that in Ting and Reimnitz (2015). The wave train propagates on a 1 in 40 plane slope and breaks as plunging breakers. The measured breaker height is 0.165 m, and the breaking depth is 0.147 m. Measurements of wave height, wave setup/setdown and wave elevation at various locations on the plane slope have been reported in Ting and Reimnitz (2015). The interested reader is referred to their publication for a detailed discussion of those results.

Three components of water and sediment particle velocities were measured simultaneously in a 3D flow volume in the outer surf zone. The same experiment was repeated 38 times. Each trial was started from still water condition and continued for 68.97 s (about 17 wave cycles). The first seven (1 through 7) trials were conducted with fluid tracers only. These trials were performed to adjust the seeding density in the test section. In the remaining trials (8 through 38), solid glass spheres were added to the test section and mixed thoroughly with the water to create a sediment-laden fluid. The latter was allowed to settle for 20 minutes before the start of a new run. Roughly the same quantity of glass spheres was added after each run to replace the net offshore transport produced by the breaking waves. During the experiment, wave elevations were measured in front of the wave generator where the still water depth is 0.283 m to record the incident wave condition. Fig. 1 shows a schematic of the experimental setup together with the locations of velocity and wave measurements.

2.2. *Volumetric three-component velocimetry technique*

A V3V system manufactured by TSI Inc. was used to measure 3C3D water and sediment particle velocities. The laser pulses emitted by a 200 mJ Dual Nd: YAG laser were expanded using two cylindrical lenses to produce a cone of illumination, which was projected through the side wall of the flume. The V3V camera was mounted underneath the flume to view the flow through a Plexiglas floor panel (Fig. 1). The measurement volume is the intersection of the field of view

(FOV) of the V3V camera and the region illuminated by the laser. The measurement volume dimensions were approximately 140 mm in the cross-shore (Y) and along-shore (X) directions. A masking tape was used to reduce the measurement volume height in the “vertical” (Z) direction (perpendicular to the plane slope) to 11 mm adjacent to the bottom. The measurement volume was centered on a still water depth of 0.115 m along the centerline of the flume to capture the impingement of the plunger and first splash-up vortices on the bottom (see Ting and Reimnitz, 2015).

Omitting a sediment bed in the experiment is analogous to the approach used in a numerical study by Vittori (2003), in which sediment particles were released in a single layer and placed at the nodes of a numerical grid next to the bottom. With this experimental setup, the flow field can be viewed through the Plexiglas bottom, and the height of the measurement volume can be reduced to a few millimeters adjacent to the bed to maximize the spatial resolution and minimize interference from entrained air bubbles, conditions that are essential for accurate measurements of bottom shear stress and velocity field induced by vortex impingement. Without an actual sediment bed, we could still investigate the role of breaker vortices on sediment suspension and transport. However, the effects of bed failure (Hsu and Hanes, 2004) and upward directed pressure gradient inside a sediment bed (Sumer et al., 2013) on the pickup process were not considered. A separate set of experiments is currently being conducted over a movable bed to determine the boundary conditions for sediment suspension.

The V3V camera is equipped with three apertures (focal length 50 mm, F-number 16) and sensors (2048×2048 pixels, 12-bit intensity dynamic range) arranged in the shape of an equilateral triangle. The sensors capture three separate images (left, right and top) of the scattering particles. When the images are combined, each scattering particle creates a unique

triangular pattern called a triplet. The centroid of the triplet gives the X and Y positions of the particle and the size of the triangle provides the Z position (Pereira et al., 2000). The relationship between the triangle size and particle's Z position is established by traversing a calibration target with a precise grid of dots through the measurement volume. The calibration was conducted in 0.25 mm increments, and the final position of the calibration target was nearly flushed with the Plexiglas bottom. This procedure allowed velocity measurements to be made very close to the bed. In the V3V coordinate system, the origin of the Z -coordinate is located at the camera with Z increasingly negative away from the camera. The positive Y -direction is onshore and the positive X -direction is across the flume toward the lasers. Note that a different coordinate system (Fig. 1) is used to report the wave measurements along the flume.

The image processing in V3V is conducted in three steps: 2D particle identification, 3D particle identification, and 3D particle tracking. To search for particles in the 2D images, local peaks in gray scale value are first identified. Each local peak is dilated to include its neighbor pixels until the local intensity reaches a defined threshold. A Gaussian intensity function is fitted to each group of pixels to determine the particle centroid position. This process also determines the particle radius and peak intensity, which are used to separate the solids and tracers based on a combination of particle spot size and brightness (Section 2.3). After phase separation, the 2D particle positions in each set of images (left, right, and top; tracers or solids) are used with the calibration results to determine the positions of individual particles in the 3D space. In the final step, the relaxation method (Ohmi and Li, 2000) is used to search for particle pairs in straddled frames (frames A and B) to obtain the 3D displacement vectors. For a detailed description of the image processing procedure, the interested reader is referred to Ting et al. (2013).

2.3 Phase separation

Yellow colored glass spheres (size range 0.09 to 0.15 mm, specific gravity 2.5) from Ceroglass were used as sediment particles. The size range was reduced to between 0.125 and 0.15 mm using the No. 100 and 120 sieves and a mechanical shaker. The fluid tracers were silver-coated hollow glass spheres (mean diameter 13 μm , specific gravity 1.3). The solids and fluid tracers were separated by a combination of particle spot size and brightness. Fig.2 shows a zoomed image from the top camera. The full image is 2048×2048 pixels and contains approximately 45000 particles. The zoomed image is approximately 400×300 pixels. Due to light scattering, the sizes of the solids and tracers in the image are much closer compared to their actual physical sizes. Still, the solids are large and bright, whereas the tracers are much smaller and/or dimmer. Because the sensors need to receive enough light to resolve the tracers, the solids are usually saturated. Fig.3 shows a typical size-brightness map from a sediment-laden flow under breaking waves. Particle spot size is calculated from the measured X and Y radii based on the area of an ellipse ($\pi \times X \text{ radius} \times Y \text{ radius}$). The size-brightness map for clear-water flow with fluid tracers only (not shown) has few particles in the green color region where the particle size is greater than 2.15 square pixels and the gray scale is greater than 3000. Therefore, all the particles in that region are considered sediment particles. These criteria were applied to both frames A and B of the images from all three sensors. The solid particles identified in the top, left and right images are then used to determine the particle positions in the 3D space as described in Section 2.2. Because the fine search in the 3D identification step requires particle positions to match within 0.5 pixels in all three images in order to identify a triplet, only a fraction (about 50%) of the solids identified in the 2D images could be matched. Using yellow colored glass

spheres reduces pixel saturation (compared with white color) and consequently improves identification of particle centroid and particle yield.

All the particles with a gray scale below 3000 are considered fluid tracers (salmon color region). Note that some fluid tracers in Fig. 3 have very large spot sizes. They are out-of-focus particles that have very low light intensity. These particles were eliminated during the triplet search because they were not picked up by all three sensors, or their positions in the 2D images exceeded the fine search tolerance. The separation of fluid tracers was applied only to the top image, which was the brightest and clearest. The 3D particle identification step then seeks out the corresponding tracer particles in the left and right images. Note that the criteria used to identify the solids are more stringent because a tracer particle could be mistaken as a solid particle if it becomes too large and too bright, and there are many more fluid tracers than solids in the flow field.

The solids identified in quiescent water were used to evaluate the phase separation algorithm and to determine the uncertainties in the X , Y and Z positions of the solids. The first 26 images in each experiment run were acquired before the incident waves arrived. In the time period between experiment runs, all the solids (fall velocity ~ 1.5 cm/s) had settled to the bottom and would be stationary, while most of the fluid tracers were still in suspension. Therefore, the position of a solid particle should be the same in frames A and B. The top two plots in Fig. 4 show the distribution of the X - Y position uncertainty of the solid particles. The abscissa is distance in the X - Y plane between the corresponding particles in frames A and B. Of the 3341 solid particle pairs identified, the mean X - Y position uncertainty is 0.02 mm with 95% within 0.064 mm. The particle velocity uncertainty is estimated assuming there is no error in the laser pulse separation time between the two frames (1.2 milliseconds). The results are shown in the bottom two plots.

The uncertainty in velocity of the solids in the X and Y directions has a mean value of 1.6 cm/s with 95% within 5.4 cm/s.

Fig.5 shows the corresponding results for the Z direction. Note that many more solid particles were identified because only frame B was used in this case; it is not necessary to find the corresponding particles in frames A and B. Most of the particles are located near the bottom of the flume ($Z = -612$ mm). Of the 8427 solid particles identified, the mean Z position is -612.11 mm with 95% below $Z = -612.42$ mm. The results for the W velocity uncertainty are not shown. It has a mean value of 9.1 cm/s with 95% within 35.2 cm/s. Hence, the uncertainty in the W velocity is 5 to 10 times greater than the uncertainty in the U and V velocities. These results show that the position of a sediment particle can be determined in still water to within ± 0.1 mm and the velocity to within ± 5 to 6 cm/s in the X and Y directions. The Z position of a sediment particle can be determined to within ± 0.5 mm. The W velocity is not accurate enough and was not used in data analysis.

A similar procedure was used to determine the measurement uncertainties in the U , V and W velocities of the fluid tracers. The mean fluid velocity uncertainty is ± 1.5 mm/s in the X and Y directions and ± 1 cm/s in the Z direction. The spatial resolution of the fluid velocity measurements is determined by the vector yields in the measurement volume. After phase separation, a typical capture produced between 800 and 1000 fluid velocity vectors per millimeter in the Z direction. The maximum resolution is about $4 \times 4 \times 1$ mm³. The randomly spaced vectors were interpolated onto a rectangular grid with 2 mm spacing in the X and Y directions and 1 mm spacing in the Z direction, resulting in about 60000 vectors per instantaneous fluid velocity field. Ensemble averaging was used to separate each measured velocity vector (U, V, W) into a wave-induced component ($U_{Wave}, V_{Wave}, W_{Wave}$) and a turbulence

component (u', v', w') (Ting and Reimnitz, 2015). The ensemble-averaged velocities were computed based on 33 experiment runs. Five experiment runs (tests 3, 5, 7, 9 and 33) were not used in computing the ensemble average because some breaking waves arrived slightly early or late. Measurement errors in turbulence velocities due to ensemble averaging and subtraction are discussed in Ting and Reimnitz (2015).

3. Experimental Results

3.1. *Topology of breaking wave vortices*

The instantaneous three-dimensional fluid velocity field of plunging regular waves has been studied experimentally by Ting and Reimnitz (2015). Their measurement volume ($140 \times 140 \times 85 \text{ mm}^3$) covered the region between the wave trough level and bottom boundary layer. Fig. 6(a) shows the iso-surface for vorticity magnitude of $\omega = 20 \text{ s}^{-1}$ for a plunger vortex generated at incipient breaking. The basic structure is a vortex loop oriented obliquely upward in the direction of wave propagation. A cross section of the vortex loop is presented in Fig. 6(b), which shows two oblique vortices rotating in opposite directions; the fluid velocity is downward between the counter-rotating vortices and upward around the outside of the vortex loop. It was found that splash-up vortices generated at the second plunge point also form vortex loops. Splash-up vortices reach the bottom quickly and create an asymmetrical impingement pattern, with strong wall-jet like flow ejecting outward and upward from the impingement zone. In both types of vortices, a strong down flow exists between the vortex loop, and the depth of penetration of the down flow is closer to the free surface the closer to the wave front. Breaking-wave-generated vortices carry large amount of turbulent kinetic energy shoreward and downward and produce large apparent shear stresses. They have a life time of about $0.5T$ where T is the wave period, and the diameter of the vortex loop is about $\frac{1}{2}$ times the local still water depth. For a detailed

description of the 3D structure of breaking wave vortices in plunging waves the interested reader is referred to Ting and Reimnitz (2015). The same incident wave condition and beach slope are used in this study, but the height of the measurement volume was reduced from 85 to 11 mm. Our focus is the near-bed fluid velocity fields created by the impact of breaking wave vortices and the resulting sediment suspension and transport.

3.2. *Sediment response time*

Our measurements showed that sediment particles settled on the bottom were lifted into suspension when breaker vortices impinged on the bottom. The surge in turbulent kinetic energy and shear stress created by the down flow continued for only 3 or 4 frames, or less than 0.5 s (7.25 frames = 1 second). The latter may be taken as the characteristic time for the flow τ_F during a suspension event. Sediment and fluid velocities would be nearly equal during sediment pickup if the response time of the sediment is much less than the characteristic time of the instantaneous flow. For low relative Reynolds number, the momentum response time τ_V of the sediment is given by $\rho_s D^2 / 18\mu$, where ρ_s and D are density and diameter of sediment and μ is dynamic viscosity of fluid (Crowe et al., 1998). With $\rho_s = 2500 \text{ kg/m}^3$, $D = 0.15 \text{ mm}$ and $\mu = 1.12 \times 10^{-3} \text{ N}\cdot\text{s/m}^2$, the response time is about 0.003 s. This is much smaller than the characteristic time of flow impingement τ_F . Hence, we expect that suspended sediment would respond almost instantaneously to changes in fluid velocity.

Fig. 7 shows a comparison of the measured sediment velocities and fluid velocities around the sediment. The fluid velocities are computed using natural neighbor interpolation (Sibson, 1981) from the measured velocities of the fluid tracers found in a $4 \times 4 \times 2 \text{ mm}^3$ box centered on the individual sediment particles. The fluid and sediment velocities in the X and Y directions are compared for one wave cycle in test 28, frames 396 to 425, which captures a strong suspension

event (see Fig. 14). Three fitted lines are shown with the measured data. The green line represents a one-to-one relationship between the sediment and fluid velocities. The red line is a linear regression through all the data, and the black line is a linear regression without the outliers. The outliers are values that differ from the fitted line by more than one and a half times the standard deviation of the sediment velocities. For the transverse (U) velocity, the red line and green line almost overlap. The regression line that includes all the data points has a slope of 1.006 and a zero-intercept. The 95% confidence interval for the slope is 0.98 to 1.03. For the longitudinal (V) velocity, the slope of the regression line with outliers included is 1.0 but there is a non-zero-intercept of 0.02 m/s. The 95% confidence interval for the slope is 0.99 to 1.03. In both plots, excluding the outliers does not make the relationship between the sediment and fluid velocities closer to one-to-one. These results indicate that the sediment and fluid velocities are nearly equal in the X and Y directions; the differences are mostly within the measurement uncertainty of the sediment particle velocities ($\approx \pm 6$ cm/s). The sediment velocity in the Z direction cannot be measured accurately with the camera viewing the flow field from below, but we expect that the difference between the sediment and fluid W velocities would be close to the fall velocity of the glass spheres, or about 1.5 cm/s. In this paper, sediment flux in the cross-shore (Y) direction is computed using the number of sediment particles measured in frame B and the mean velocities of fluid tracers around the sediment.

3.3. *Sediment suspension by breaking wave vortices*

To help understand the results presented in this section, we first present some time series of suspended sediment load, fluid velocity, turbulent kinetic energy (TKE), and sediment flux from test 21 in Fig. 8 together with examples of measured velocity field and sediment distribution in Fig. 9. In Fig. 8, the abscissa is time (29 frames = 4 seconds). The top plot shows the number of

sediment particles identified in each frame. The second plot shows the longitudinal (V) and vertical (W) components of fluid velocity around the sediment. The fluid velocity at each sediment particle location is computed using natural neighbor interpolation from the measured velocities of the fluid tracers found in a $4 \times 4 \times 2 \text{ mm}^3$ box centered on the sediment particle. The interpolated fluid velocities from all the sediment particle locations are then averaged and plotted. The interpolated fluid velocities are also used to compute the turbulent kinetic energy of the fluid at the positions of the sediment particles. The mean TKE from all the sediment particle locations is shown in the third plot. The bottom plot shows the sediment flux computed as the product of suspended sediment concentration (total number of sediment particles/size of measurement volume) and average fluid velocity from all the sediment particle locations.

Several important points should be noted in Fig. 8. Each measurement record contains 500 frames (0 to 499) starting from still water condition. The first wave arrives at the measurement volume around frame 50. Suspended sediment load and turbulent kinetic energy are low in the first few wave cycles until a steady breaker position was established just offshore of the measurement volume (Fig. 1). V3V measurements showed that breaker vortices impinging on the bottom was the primary cause of sediment suspension. Small suspension events were observed when weaker and/or smaller vortices impinged on the bottom (e.g., frame 224), or when part of a large vortex was captured (e.g., frames 171 and 343). The high suspended sediment load seen in frame 198 was produced by a large vortex (Fig. 9) impacting inside the measurement area. No vortices were captured in some wave cycles (e.g., frames 250 to 278) and consequently suspended sediment load was low. The second plot in Fig. 8 shows that suspension events are associated with upward fluid velocities around the sediment. Note that fluid velocities are positive downward. The third plot shows that suspension events are also associated with high levels of turbulent kinetic energy

around the sediment. However, when only part of a vortex was captured inside the measurement volume fewer suspended sediment particles would be detected although the turbulent kinetic energy of the fluid around the sediment could be quite high (e.g., frame 341). The fourth plot shows the sediment flux in the cross-shore and vertical directions. Sediment flux is generally onshore under the wave crest and offshore under the wave trough. No breaker vortex was captured in frames 250 to 278. This wave cycle may be used as a baseline for comparison with other wave cycles when breaker vortices impinged on the bottom and produced enhanced onshore or offshore transport through the measurement volume. The net direction of sediment transport over one wave cycle is dependent on the near-bed velocity field created when a breaker vortex impacts the bottom, as well as the phase relationship between wave-induced velocity and vortex-induced sediment suspension; this will be discussed.

A limitation of the V3V system is its small FOV. The measurement area is about $140 \times 140 \text{ mm}^2$ in the cross-shore (Y) and along-shore (X) directions. The impingement zone of a breaker vortex is often larger than this, and after reaching the bottom the vortex would continue to travel onshore until flow reversal. Hence, the evolution of a vortex may not be captured completely in a single event. It is not feasible to move the camera along the flume to follow the movement of vortices. The fine search tolerance in V3V measurements is about 0.5 pixels. Any small vibrations of the camera will upset the calibration and consequently result in poor triplet yields. However, since the locations of vortex impingement varied from wave to wave, we can study the measured velocity fields in different experiment runs to piece together a more complete picture of the interactions of vortices with the bottom.

Fig. 10 shows a jet/splash sequence from the 12th wave cycle; other wave cycles at steady state are similar. These still frames were extracted from a video recording taken separately from the

velocity measurements. The first plunge point is located just outside the image area. The sequence shows the generation of the first and second splash-up vortices after the plunger vortex was already generated. The vortex impinging on the bottom inside the measurement area is the first splash-up vortex. Fig. 11 shows the measured velocity fields and distributions of suspended sediment in the same wave cycle from test 27. The velocity fields are shown at a height of 2 mm above the bottom, but the solids include all the sediment particles captured inside the measurement volume. The vortex reaches the bottom between frames 398 and 399. Measured fluid velocities in frame 399 are downward in the impingement zone (red contour), and upward in the wall-jet region (blue contour) where the down flow is deflected outward and upward. Most of the suspended sediment is located in the wall-jet region. The transient event lasted for only a fraction of a second when sediment particles were lifted from the bottom and ejected from the impingement zone (frames 399 to 402). Fig. 12 shows the temporal variations of suspended sediment load and several flow parameters obtained from the measured velocity fields. The measured data are presented for one complete wave cycle from frames 395 to 423. These results may be compared with frames 250 to 278 in Fig. 8 when no breaker vortex impinged on the bottom inside the measurement volume. In that wave cycle, the number of suspended sediment particles captured is less than 40, the average vertical velocity around the suspended sediment is close to zero, the average turbulent kinetic energy around the sediment is below $20 \text{ cm}^2/\text{s}^2$, and the average vorticity magnitude around the sediment is around 10 s^{-1} .

Referring to Fig. 12, the top plot shows that the total number of suspended sediment particles increases rapidly in frame 399, reaches the maximum in frame 400, then decreases. Sediment suspension has just started in frame 399; there are more sediment particles in the bottom 2 mm ($Z = -612$ to -614 mm) compared to the top 9 mm of the measurement volume ($Z = -614$ to -623

mm). The second plot from the top shows the average longitudinal (V) and vertical (W) velocities of the fluid from all the sediment particle locations, and the average longitudinal velocity of the sediment particles (V_{Sed}). The measured longitudinal fluid velocity V reaches the maximum positive in frame 397 when the wave front passed through. For reference, the ensemble-averaged fluid velocity (not shown) reaches the maximum positive in frame 398. The second plot also shows that the fluid W velocity is downward (positive) in frame 398, but changes to upward (negative) in frame 399, and remains upward until frame 405. In addition, the average sediment velocity is close to the average fluid velocity around the sediment, confirming that sediment particles responded almost instantaneously to changes in fluid velocity. The third plot shows the average turbulent kinetic energy and average total and turbulent shear stresses of the fluid from all the sediment particle locations. These apparent shear stresses represent the vertical fluxes of horizontal fluid momentum. Total shear stress is computed using the measured velocity (U, V, W) and turbulent shear stress is computed using the turbulence velocity (u', v', w') as shown in the figure caption. The difference between these two velocities is the ensemble-averaged or wave-induced velocity ($U_{Wave}, V_{Wave}, W_{Wave}$). The latter includes the time-averaged velocity or undertow. Turbulent kinetic energy reaches a peak in frame 399 or 400, at about the same time when suspended sediment load reaches the maximum. Total shear stress and turbulent shear stress have the same sign as vertical velocity during vortex impingement (frames 398 to 405), emphasizing the role of vertical velocity in transporting turbulent fluid toward or away from the bottom. The fourth plot shows that sediment suspension is associated with high levels of fluctuating vorticity. The vorticity magnitude returns to an ambient level of about 10 s^{-1} at the end of the wave cycle. The bottom plot shows the sediment fluxes in the longitudinal and vertical directions. Sediment pickup lasted for less than 1 s from frames 399 to 404 when the

sediment flux is upward (negative). Both cross-shore and vertical sediment fluxes reach the maximum in frame 400 at the same time as suspended sediment load.

Contour plots of turbulent kinetic energy k , turbulent shear stress τ , total shear stress T , and vorticity magnitude ω for frame 400 are presented with the distribution of suspended sediment in Fig. 13. After the wave crest has passed, the wave-induced velocities are small compared to the turbulence velocities. Consequently, the distributions of total shear stress and turbulent shear stress are very similar. Shear stresses are negative when vertical velocity is upward (see caption for Fig. 12). Large negative shear stresses were produced when high velocity fluid was ejected from the bottom. This occurs in the wall-jet region where the down flow is deflected outward and upward, and most of the suspended sediment is found in this region. Much fewer suspended sediment is found in the impingement zone where the vertical velocity is downward. The correlation of suspended sediment load with vorticity magnitude is not as good as with apparent shear stresses. However, we will present two other cases before examining the correlation coefficients between sediment concentration and the individual flow parameters.

As a second example, Fig. 14 presents the measured velocity fields and distributions of suspended sediment in the same wave cycle from test 28. This breaker vortex is similar in size to the one shown in Fig. 11 but its 3D structure is different. The breaker vortex in Fig. 14 has an asymmetrical impingement pattern with two counter-rotating vortices behind the down flow. The counter-rotating vortices form the two legs of a vortex loop tilted obliquely upward in the direction of wave propagation (see Fig. 6(a)). The vortex loop breaks up after it impacts the bottom (Frames 401 and 402). The clockwise vortex has left the FOV after frame 399, but we can follow the movement of the counter-clockwise vortex for some time. Fig. 15 presents the distribution of suspended sediment and contour plots of vorticity magnitude from frames 399 to

414. As seen, sediment particles are trapped by the counter-clockwise vortex and stay in suspension until the vortex is dissipated around flow reversal in frame 407.

Fig. 16 presents the temporal variations of suspended sediment load and several measured flow parameters around the sediment. The top plot shows that the number of suspended sediment particles increases rapidly between frames 398 and 399 when the vortex hit the bottom. Very few sediment particles were in suspension in frame 398, but they were suddenly subject to high downward (positive) fluid velocities (second plot). Average fluid velocity around the suspended sediment changes from downward (positive) to upward (negative) in frame 399 and simultaneously large number of sediment particles were lifted from the bottom. Suspended sediment load remains very high in frames 400 and 401. After frame 402, the down flow had diminished and suspended sediment load decreases rapidly (first plot). The sediment particles in suspension were surrounded by turbulent fluid with an average upward velocity of 2 to 3 cm/s until frame 405 (second plot). This may be compared with the sediment fall velocity of about 1.5 cm/s. The fourth plot shows that the fluid motion around the suspended sediment is characterized by high levels of fluctuating vorticity. This can also be seen in the contour plots of vorticity magnitudes shown in Fig. 15. These results suggest that the mechanism for keeping sediment in suspension is associated with vortex motions. The phenomenon was first investigated experimentally by Tooby et al. (1977) and analyzed in detail in Nielsen (1992). Nielsen (1992) showed that suspended sediment trapped by a vortex spends more time in the upward moving parts of the flow than in the downward moving parts. He noted that the trapping mechanism would work for sediment particles with settling velocity smaller than the maximum velocity in the vortex. Sediment trapping by vortices was observed in all our experiment runs; the trapped sediment was released after the vortices had dissipated. The bottom plot shows

that, compared to Fig. 12, the asymmetrical impingement pattern produced an enhanced onshore transport of suspended sediment in the early part of the wave cycle. As in Fig. 12, the average sediment velocity is close to the average fluid velocity around the sediment (second plot).

Fig. 17 presents the distribution of suspended sediment with contour plots of turbulent kinetic energy and total shear stress from test 28, frames 399 and 400. Most of the suspended sediment in frame 399 is located in the wall-jet region where the apparent shear stress is negative (blue contour), but many sediment particles are also found in the impingement zone where the apparent shear stress is positive (red contour). Since sediment particles cannot be lifted from the bed without an upward fluid velocity, we speculate that those particles were put into suspension by the deflected flows. They were then left behind over the impingement zone as the latter moved onshore with the breaking wave.

The breaker vortices produced by plunging waves create a strong deflected flow around the front and sides of the impingement zone. Fig. 18 shows an important case in which a large vortex reached the bottom just offshore of the measurement volume then continued to travel onshore. Video recording showed that this vortex was in fact a plunger vortex generated at incipient breaking. Although most of the vortices captured were splash-up vortices generated at the second plunge point, some plunger vortices were also captured due to slight variations in the location of the breaking point from wave to wave induced by low-frequency motions in the flume. The distributions of suspended sediment are presented in Fig. 18 with the measured velocity fields and contour plots of turbulent kinetic energy (top plots), total shear stress (middle plots) and vorticity magnitude (bottom plots) at a height of 2 mm above the bottom. As seen in frame 428, most of the suspended sediment is carried by the deflected flow where the apparent shear stress is negative (middle plot), while large areas with high turbulent kinetic energy contain

few sediment particles (top plot). Hence, the distribution of suspended sediment correlates better with total shear stress than with turbulent kinetic energy in this case. High levels of fluctuating vorticity were also measured in the deflected flow in front of the impingement zone (bottom plot), but fluid particles did not rotate about a vortex center as in a vortex loop so sediment particles were not trapped and would settle out quickly. Fig. 19 presents the temporal variations of suspended sediment load and several measured flow parameters around the sediment for the entire wave cycle. The top plot shows that the number of suspended sediment particles increases and decreases rapidly around frame 428 when the deflected flow swept through the measurement volume. The second plot shows that sediment particle velocities are close to the fluid velocities around the sediment, and that the suspension process is associated with negative (upward) fluid velocities around the sediment. The third plot shows that the fluid particles around the suspended sediment have high turbulent kinetic energy from frames 427 to 429. However, the suspended sediment load is much higher in frame 428 than in frames 427 and 429 (top plot). Therefore, turbulent kinetic energy is not a reliable measure of suspended sediment concentration. The variations in total and turbulent shear stresses more closely reflect the variation in suspended sediment load and may be better indicators. The fourth plot shows that the temporal variation of vorticity magnitude is similar to that of the turbulent kinetic energy. The bottom plot shows that the onshore sediment flux produced by the deflected flow is much larger compared to the other two cases (Figs. 12 and 16).

The flow parameters presented in Figs. 12, 16 and 19 are mean values from all the sediment particle locations. We have also studied the distributions of individual flow parameters among the sediment particles in each frame (LeClaire, 2015). Those results showed that sediment suspension was associated with high levels of turbulence activities and in particular large upward

fluid velocities. For example, the histogram for the W velocity showed that 53% of the suspended sediment in frame 399, test 27 (Fig. 11) was surrounded by negative (upward) fluid velocities; the mean value of the upward velocity is -5.9 cm/s. The number of suspended sediment particles reached the maximum in frame 400, and the percentage of sediment particles surrounded by upward fluid velocities increases to 68% with a mean value of -6.4 cm/s. From frames 401 to 404, the percentage of sediment particles with upward fluid velocities stays about the same at around 70% while the average upward fluid velocity around the sediment decreases steadily from -5.4 to -3.0 cm/s. The latter is still considerably greater than the sediment fall velocity of about +1.5 cm/s. After frame 404, the number of suspended sediment particles varies slowly with time until the next breaker arrives. We note that the measurement volume contains only about 10% of the water column. A plot of $\log(N)$ versus Z , where N is the number of suspended sediment particles in a 2-mm-thick slice, does not provide conclusive evidence whether the measured sediment profiles are Rouse-shaped or exponential, although the observed flow structures would have suggested a convective transport process.

3.4. *Relationships between sediment concentration and turbulent flow parameters*

In this section, we examine the correlation coefficients (R -values) between suspended sediment concentration and several flow parameters and their P -values. A P -value is the probability of getting a correlation as large as the observed value by random chance, when the true coefficient is zero. If the P -value is less than 0.05 or 5%, the observed correlation coefficient (R -value) is considered significant (Freedman, 2009). The $136 \times 136 \times 11 \text{ mm}^3$ measurement volume was divided into sixteen $34 \times 34 \times 11 \text{ mm}^3$ subzones. To investigate the relationships between suspended sediment concentration and different flow parameters during sediment pickup, we counted the number of sediment particles with upward fluid velocities in each subzone. For each

flow parameter, we interpolated its values at the sediment particle positions using the measured fluid velocities around the particles. Then, we computed a mean value for each subzone. The correlation coefficient between suspended sediment concentration and the flow parameter was computed using 16 data points, one from each subzone. Increasing the number of subzones generally reduces the R -values but also increases the degrees of freedom, which in turn reduces the critical values for the correlation coefficients and thus does not change the overall conclusion.

Fig. 20 shows the R - and P -values for test 27, frames 399 to 405. Vertical velocity, total shear stress and turbulent shear stress have P -values less than 0.05 from frame 399 to 402, which indicate that sediment pickup is significantly related to these three parameters during flow impingement and deflection. The P -value is much greater than 0.05 for the turbulent kinetic energy therefore the two variables are unrelated. Vorticity magnitude also has low P -values, but this is likely due to the high levels of fluctuating vorticity in the deflected flow. Fig. 21 shows the corresponding results for test 28 when large number of sediment particles are trapped by a counter-clockwise vortex. The vorticity magnitude has P -values significantly less than 0.05 from frame 399 to 404, which indicates that counter-rotating vortices play an important role in picking up sediment particles and keeping them in suspension. The number of suspended sediment particles is not correlated to the other flow parameters during flow impingement, which have high P -values in frames 399 and 400. All the flow parameters studied have lower P -values in frames 401 and 402, after the down flow has diminished. The low P -value for the turbulent kinetic energy after frame 402 is likely associated with the counter-clockwise vortex, which is the main source of turbulent kinetic energy in the flow field. Fig. 22 shows the results for test 15, frame 426 to 431. Vertical velocity, total shear stress, and turbulent shear stress have P -values

close to or less than 0.05 when the deflected flow swept through the measurement volume (frames 428 and 429). The correlations with the vorticity magnitude and turbulent kinetic energy are not as good. Figs. 20 to 22 indicate that different flow mechanisms are responsible for sediment pickup and distribution in different parts of the impact flow field. The deflected flow is primarily responsible for sediment suspension in the wall-jet region around the impingement zone, but the vortex loop also entrains large quantities of sediment. Turbulent kinetic energy by itself is not a reliable indicator of suspended sediment concentration because high turbulence intensity can be found in both the impingement zone and wall-jet region, whereas upward fluid velocity is essential for lifting sediment particles from the bed and carrying them into suspension.

The role of coherent structures in sediment entrainment by turbulent shear flows near walls has been linked to the bursting phenomena (Kline et al, 1967; Corino and Brodkey, 1969; Grass, 1971). To quantify bursting events, the instantaneous Reynolds stress is divided into four quadrants based on the signs of the streamwise and vertical components of turbulence velocity. In the VW coordinate system and under onshore mean flow, $v' > 0, w' < 0$ corresponds to quadrant Q_1 or outward interactions; $v' < 0, w' < 0$ corresponds to quadrant Q_2 or ejections; $v' < 0, w' > 0$ corresponds to quadrant Q_3 or inward interactions; and $v' > 0, w' > 0$ corresponds to quadrant Q_4 or sweeps. Note that the signs for v' are reversed under offshore mean flow. From laboratory observations of sediment entrainment by turbulent flows, Sutherland (1967) concluded that sediment grains cannot be lifted from the bed without the presence of turbulent fluctuations adjacent to and directed toward the bed. He hypothesized that when a turbulent eddy impinges onto a granular surface, the interaction between the fluid motion in the eddy and the individual grains would result in grain entrainment. He postulated that at high rates

of sediment transport, the resulting force on the grains will be inclined at a small angle away from the bed to lift sediment particles off the bed. Dwivedi et al. (2010, 2011) conducted PIV measurements over single fixed and single movable sphere embedded in a bed of identical spheres in open-channel flows. They measured the instantaneous pressure on the surface of the fixed sphere at locations upstream of, above, downstream of, and below the sphere. They found that entrainment of the sphere coincides with the occurrence of sweep (Q_4) events, which produce high vertical and horizontal pressure gradients on the sphere. Quadrant analysis of drag and lift forces further revealed higher probability of occurrence of high magnitude force induced by sweep events. On the contrary, ejection (Q_2) events, although they also contribute positively to the instantaneous Reynolds stress ($v'w'$), would reduce the drag force due to reduced streamwise velocities.

Based on the traditional classification scheme, our V3V measurements indicate that sweeps ($v' > 0, w' > 0$) and inward interactions ($v' < 0, w' > 0$) cause the initiation of sediment suspension. These events are associated with the impingement of down flow on the bottom (Figs. 11 and 14). Figs. 12 and 16 show that the number of suspended particles increases tremendously after frame 398, when sediment particles were suddenly subject to large positive (downward) vertical velocities. However, there are some important differences between the coherent structures in turbulent shear flows near walls and breaking-wave-induced vortices. Bursting phenomena occur mainly in the wall region. The coherent structures generated in the wall boundary layer are of a similar scale to the bed particles (Dwivedi et al., 2011). On the contrary, the sizes of breaking wave vortices are comparable to the local wave height and water depth. Depending on the timing of vortex impingement on the bottom, the fluctuating velocities in breaking wave vortices can also be many times greater than the organized wave-induced

velocities. Nezu and Nakagawa (1993) used the term large-scale vortical motions to differentiate coherent structures in the outer region of open-channel flows from the bursting eddies generated in the wall region. The former includes horizontal rollers in hydraulic jumps and horseshoe vortices around submerged obstacles, which are more akin to the breaking-wave-generated vortices studied here. Further research is needed to understand the structure of wave bottom boundary layer disrupted by breaking wave vortices.

3.5. *Relationship between sediment flux and turbulent kinetic energy flux*

Using LDA measurements, Ting and Kirby (1994) computed the correlation coefficient between phase-averaged velocity and turbulent kinetic energy for spilling and plunging regular waves on a plane slope. They found that the correlation coefficient is negative below the wave trough level for spilling waves but positive for plunging waves, which means that turbulent kinetic energy is transported seaward by spilling waves but landward by plunging waves below the wave trough level. They suggested that cross-shore sediment transport and the types of beach profiles (erosive or accretive) are related to the temporal distribution of turbulence and specifically its phase relationship with the organized wave-induced velocities.

The heuristic model by Dean (1973) predicts that wave conditions are erosional if the value of wave-height-to-wavelength ratio in deep water H_0/L_0 exceeds $1.7\pi w/gT$, where w is sediment fall velocity and T is wave period. With $w = 1.5$ cm/s and $T = 4$ s, the critical value of H_0/L_0 is 0.002. Hence, the wave condition ($H_0/L_0 = 0.0033$) used in this study would produce an erosive profile on a sandy beach. The net sediment flux in the last 10 complete wave cycles of each experiment run was determined from the measured data. The result is always negative. This is consistent with visual observation that glass spheres were deposited offshore of the measurement area after each experiment run.

Although net sediment flux over a wave train was directed offshore, onshore sediment transport did occur in some wave cycles. Fig. 23 shows the distribution of onshore sediment transport events among 29 experiment runs. The largest number of onshore transport events measured over ten wave cycles is 5 in one experiment run. Most experiment runs (18 out of 29) produced only 1 or 2 onshore sediment transport events, and 3 runs produced only offshore transport events. Out of a total of 290 wave cycles in 29 experiment runs, there were 54 onshore and 234 offshore sediment transport events; two wave cycles produced zero net transport. The mean value of the net sediment flux for the onshore transport events is $5.8 \text{ particles/cm}^2$, compared to $-7.7 \text{ particles/cm}^2$ for the offshore transport events. There were not only more offshore sediment transport events, but the offshore transport events carried more sediment particles on average compared to the onshore transport events. Hence, the movement of suspended sediment through the measurement volume was predominantly offshore for these wave conditions.

Net sediment flux and net TKE flux over one wave period are plotted against each other for all 290 wave cycles from the 29 experiment runs in Fig. 24(a). TKE flux is defined as the flow of turbulent kinetic energy through a unit area perpendicular to the cross-shore direction. The TKE flux is computed first at the position of each sediment particle by multiplying the TKE per unit volume $\rho(u'^2 + v'^2 + w'^2)/2$ and the longitudinal fluid velocity V . Here, ρ is fluid density, and the fluid velocities u', v', w' and V are interpolated at the sediment particle position from the measured fluid velocities around the sediment (see Section 3.3). The results are averaged over all the sediment particles in the measurement volume and summed over the wave period to yield the net flux. Note that only measured fluid velocities around the sediment, and not in the entire measurement volume, are used to calculate the TKE flux.

Since the experiment was conducted without a sediment bed, the number of sediment particles put into suspension by one breaker would be affected by the amount of sediment deposited in the measurement area by previous breakers and thus is not a function of flow conditions alone. Some of the scatter seen in Fig. 24(a) is probably due to this variability in sediment availability. Nevertheless, the strong correlation between net sediment flux and net TKE flux is unmistakable. The R -value of the correlation is 0.77 with a P -value close to zero, which indicates that the relationship is statistically significant. The R -value increases to 0.9 if the net sediment flux and net TKE flux over the individual wave cycles are ensemble-averaged over the 29 experiment runs (Fig. 24(b)). Fig. 24(a) shows that positive (onshore) net sediment flux is associated with positive (onshore) net TKE flux. However, positive net TKE flux does not always produce onshore sediment transport; many offshore sediment transport events occurred with positive net TKE fluxes. Net sediment flux is always positive only when the net TKE flux is greater than about 4 kg/s^2 .

Fig. 24(a) shows that there are more offshore than onshore sediment transport events. For example, there are sixty nine (69) breaking waves with offshore net sediment flux over one wave cycle greater than $10 \text{ particles/cm}^2$ (the mean value is $-13.9 \text{ particles/cm}^2$), while only nine (9) such events for onshore sediment transport (the mean value is $18.6 \text{ particles/cm}^2$). Inspection of the measured velocity fields showed that all the onshore sediment transport events with net sediment flux over one wave cycle greater than $10 \text{ particles/cm}^2$ are associated with strong shoreward deflected flows in front of the impingement zone. For example, the turbulence event shown in Fig. 18 (test 15, frames 425-453), which is the largest onshore sediment transport event in Fig. 24(a), produced a net sediment flux of $30.1 \text{ particles/cm}^2$ and a net TKE flux of 8.2 kg/s^2 over one wave cycle. Three other onshore sediment transport events in Fig. 24(a) occurred in the

same wave cycle (frames 280-309) but in different experiment runs (tests 17, 30 and 35). They produced similar net sediment fluxes (about 20 particles/cm²), but the net TKE flux varies over a wide range from 0.9 to 6.9 kg/s². The variations in net TKE flux are due to several factors including the distribution of turbulence velocities (both magnitude and direction) around the sediment, and differences in phase relationship between vortex impingement and the mean flow. Similarly, four strong offshore sediment transport events with net sediment flux over one wave cycle equal to or greater than 20 particles/cm² occurred in tests 20, 30, 32 and 34. In all four events, strong offshore-directed deflected flows and/or counter-rotating vortices were captured in the measurement area.

To gain a better understanding of the flow conditions that contribute to onshore or offshore sediment transport, the data presented in Fig. 24(a) are re-plotted in five subgroups (*A* to *E*) in Fig. 25. Case *A* corresponds to the situation when no downburst or deflected flow is captured inside the measurement area. Case *B* occurs when a breaker vortex reaches the bottom just offshore of the measurement area (e.g., Fig. 18). Case *C* occurs when a breaker vortex impinges on the bottom just onshore of the measurement area (e.g., Fig. 9, frame 342). Case *D* occurs when a breaker vortex impacts to the left or right of the measurement area (e.g., Fig. 9, frame 171). Case *E* occurs when a breaker vortex impinges inside the measurement area (e.g., Fig. 9, frames 198 and 224; Figs. 11 and 14). These five cases account for approximately 15%, 31%, 23%, 19% and 11% of the data points in Figure 24(a), respectively.

In case *A* (top plot), net TKE flux over one wave cycle is small and ranges mostly between -1 and 1 kg/s² with a mean value of -0.11 kg/s². The negative net TKE fluxes are due to offshore transport of residual turbulence in the flow field. Small amounts of positive net TKE fluxes were measured in some wave cycles. They are associated with pseudo turbulence created by the ensemble

averaging process. Due to low-frequency motions in the flume, the arrival time of breaking waves may vary slightly from wave to wave and from one experiment run to another. These experimental fluctuations produce errors in the separation of mean flow and turbulence by ensemble averaging. Larger errors typically occur under the wave front when the wave-induced velocity changes rapidly with time. Obviously, pseudo turbulence cannot entrain sediment. Sediment particles are kept in suspension by residual turbulence and carried offshore by the mean flow. Net sediment flux and net TKE flux are poorly correlated. All the measured net sediment fluxes in this case are negative with a mean value of $-5.7 \text{ particles/cm}^2$.

In case *B* (second plot), turbulence velocities have a predominantly shoreward direction. They are associated with the deflected flows in front of the impingement zone, which carry both sediment and turbulent kinetic energy onshore (Fig. 18). Net sediment flux is well correlated with net TKE flux. However, the onshore-directed turbulence velocities have to be very strong and coincide with the onshore wave-induced velocities so that the amount of suspended sediment carried onshore would exceed that carried offshore after flow reversal to produce a net onshore transport over one wave cycle. The mean values of net TKE flux and net sediment flux are 1.8 kg/s^2 and $1.4 \text{ particles/cm}^2$, respectively.

Case *C* (third plot) refers to those wave cycles when breaker vortices impact the bottom just onshore of the measurement area. Turbulence velocities in the measurement volume were predominantly seaward. In some breaking waves, one or both of the counter-rotating vortices were also captured. Sediment particles trapped by these vortices stayed in suspension after the down flow had ceased. The trapped particles were transported offshore after flow reversal. All the net sediment fluxes are negative in this case. The mean value is $-11.1 \text{ particles/cm}^2$. Net TKE flux and net sediment flux are also well correlated. The mean net TKE flux is -1.4 kg/s^2 . Note that

some TKE fluxes have small positive values. They are associated with the onshore transport of pseudo turbulence discussed above.

Case *D* (fourth plot) corresponds to the situation when breaker vortices impact the bottom to the left or right of the measurement area. Both onshore and offshore turbulence velocities were measured around the sides of the impingement zone. Net sediment fluxes over one wave cycle are mostly offshore; the mean value is -6.4 particles/cm². Net sediment flux and net TKE flux are well correlated. Net onshore sediment transport occurred in a few breaking waves with large positive net TKE fluxes. The mean value of the net TKE fluxes is close to zero.

Case *E* (bottom plot) occurred in a small number of breaking waves (about 11%) when a breaker vortex impinged directly inside the measurement area. The vortex then continued to travel onshore. Net sediment fluxes over one wave cycle are mostly negative; the mean value is -7.6 particles/cm². Net TKE fluxes are also mostly negative; the mean value is -0.57 kg/s². In a few breaking waves, positive net TKE fluxes produced a small amount of net onshore sediment transport.

Fig. 25 shows that different parts of breaking wave vortex produce different effects on turbulence and sediment transport. The deflected flow in front of the impingement zone is primarily responsible for transporting turbulent kinetic energy and suspended sediment onshore, while sediment particles around the sides and behind the impingement zone are generally carried offshore. Counter-rotating vortices have a long life time compared to the down flow. Trapped particles are released after the vortices have dissipated, then carried offshore by the mean flow. Sediment trapping by vortices was observed in all the experiment runs when counter-rotating vortices were captured. Therefore, the process plays an important role in onshore/offshore

sediment transport. For the wave condition studied, the overall effect of vortex impingement and its interaction with the mean flow was to produce net offshore sediment transport. This can be seen in case *E* when breaker vortices impinged inside the measurement area. Our measurements show that the timing of vortex impact and the resulting near-bed velocity field are important factors in determining whether net sediment transport would be onshore or offshore over a wave cycle. As shown in Fig. 25, only the strong breaker vortices produced by the wave train are capable of transporting sediment onshore. The strong vortices carry large amount of turbulent kinetic energy and reach the bottom when the wave-induced velocity is directed onshore. For example, the flow impingement shown in Fig. 9, frame 198 occurs two frames later in the wave cycle and has a more symmetrical pattern compared to the flow impingement shown in frame 224 of the same experiment run. In the former case, the net sediment flux over one wave cycle is $-7.6 \text{ particles/cm}^2$ and the net TKE flux is -0.53 kg/s^2 . In the latter case, the fluxes are $2.8 \text{ particles/cm}^2$ and 1.9 kg/s^2 , respectively. In another example, the net sediment flux over one wave cycle is $-6.8 \text{ particles/cm}^2$ for the downburst shown in Fig. 11 but it is close to zero for the downburst in Fig. 14.

4. Discussion

We have measured sediment particle position, sediment particle velocity and fluid velocity simultaneously under plunging regular waves using a V3V system. The two-phase flow measurements revealed the role of breaking-wave-induced vortices in sediment pickup and distribution. These processes would be difficult to understand using point measurements alone because sediment particles are entrained and kept in suspension by large eddies that have coherent flow properties over its spatial extent. In this section, we discuss these measurements in relation to published work and current understanding of sediment transport in breaking waves.

Many researchers have found that a significant portion of the suspended load in the surf zone is generated by breaking waves (e.g., Kana, 1979; Beach and Sternberg, 1996). Our experiment was conducted on a fixed bed. Glass spheres were replenished before each experiment run to create a sparse layer of sediment particles in the test section for suspension by breaking waves. This is analogous to the approach used in a numerical study by Vittori (2003), who released sediment particles in a single layer and placed them at the nodes of a numerical grid next to the bottom. Under this artificial condition, we found that significant sediment suspension occurred only when breaker vortices reached the bottom. For non-breaking waves, Vittori (2003) found that sediment particles are picked up from the bed during the breakdown of low-speed streaks generated in the bottom boundary layer. Her numerical results show that the pickup rate is better correlated with turbulence production than with turbulent kinetic energy or bed shear stress. She hypothesized that the breakdown of low-speed streaks causes an increase of turbulence activity, which produces large drag and lift forces on the sediment grains. In breaking waves, strong down flows accompany the impingement of breaker vortices on the bottom. The movement of high momentum fluid toward the bed is analogous to the sweep events in turbulent shear flows near walls. Sweep events produce large drag and lift forces on bottom sediment and contribute significantly to sediment entrainment in open-channel flows (Dwivedi, 2011a,b). In our experiments, entrained particles were carried away from the bed in the wall-jet like flow deflected outward from the impingement zone. Measured suspended sediment concentrations were well correlated with the vertical velocity in the deflected flow region. Suspended sediment concentrations were also well correlated with the vorticity magnitude when a large vortex loop reached the bottom, which suggests that counter-rotating vortices play an important role in picking up sediment particles and keeping them in suspension. Suspended sediment concentrations did

not correlate well with turbulent kinetic energy, unless counter-rotating vortices were the primary source of turbulence energy in the flow field. Our results are consistent with the field measurements by Aagaard and Hughes (2010), who found that suspended sediment concentrations are more closely related to the vertical than the horizontal velocity variance in plunging breakers and surf bores. Near the bottom, the vertical velocities are small in magnitude compared to the horizontal velocities. The horizontal velocity variance is essentially a measure of the turbulent kinetic energy, which is not simply related to suspended sediment concentration. This is because high sediment concentration is not always found with high turbulence intensity around the sediments, and flow regions with high turbulence intensity may not contain high concentrations of suspended sediment (e.g., Figs. 13 and 17, frame 400). Our measurements indicate that total or turbulent shear stress are better parameters for locating sediment suspension events. These apparent shear stresses combine the effects of horizontal and vertical fluid velocities. Therefore, their distributions can better represent the three-dimensional flow conditions for sediment pickup.

Aagaard and Hughes (2010) measured large downward velocities followed immediately by upward-directed velocities under the leading face and crest of a breaker. They interpreted the event as a breaker vortex plunging very close to or on the instrument station. This sudden change in the direction of vertical velocity can be seen in Figs. 12 and 16 and is induced by the outward deflection of down flow impinging on the bottom. The down flow is located between the two legs of the vortex loop descending to the bottom (Ting and Reimnitz, 2015). Down flows impinge on the bottom and create high turbulence velocities perpendicular to the bed, without which sediment particles cannot be lifted from the bottom. Therefore, modeling the intensity and

duration of down flows would be an important aspect in modeling sediment suspension under breaking waves.

Several studies (e.g., Scott et al., 2009; Aagaard and Hughes, 2010) have concluded that breaking-wave-induced vortices would enhance onshore or offshore sediment transport depending on the phase relationship between the longitudinal fluid velocity and sediment suspension events. This is the basis of the heuristic model proposed by Dean (1973) for predicting erosional or accretive beach profiles. Ting and Kirby (1994) found fundamental differences in the structure of turbulence in spilling and plunging waves and discussed their implications on cross-shore sediment transport and beach transformation. They used turbulent kinetic energy as a surrogate for suspended sediment concentration and showed that net turbulence energy transport is onshore under plunging waves, but offshore under spilling waves below the wave trough level. The two-phase flow measurements in this study confirm that there is indeed a relationship between suspended sediment transport and turbulent kinetic energy transport. For both the individual waves and their ensemble averages, we found that positive (onshore) net sediment flux is always associated with positive (onshore) net turbulent kinetic energy flux, and that the two quantities are correlated with a high degree of certainty. However, net offshore sediment transport also occurs with net onshore turbulence energy transport, unless the net turbulence energy flux exceeds a large positive threshold. Several factors may have contributed to this phenomenon. First, a small amount of pseudo turbulence is transported onshore under the wave front. Second, the fluid particles transporting suspended sediment shoreward typically carry more turbulent kinetic energy compared to the fluid particles transporting sediment seaward. Third, turbulence intensity around the sediment can be quite high even when suspended sediment concentration is low. Note that although high turbulence velocities may be required to mobilize bottom

sediments, entrained particles can be kept in suspension by other mechanisms including trapping by vortices and the loitering effect (Nielsen, 1992), which do not necessarily involve very high turbulence intensity. Therefore, turbulent kinetic energy by itself is not a reliable indicator of near-bed suspended sediment concentration. This also implies that not all the turbulent kinetic energy in the fluid motion near the bed is involved in transporting sediment.

The importance of relative timing between sediment suspension and the wave velocity phase in enhancing the direction of onshore or offshore transport is well known. A factor that has largely been overlooked is the near-bed velocity fields created by the impact of breaking wave vortices. We recorded about four times more offshore sediment transport events compared to onshore transport events for the wave condition studied. The large onshore transport events were all produced by breaker vortices impinging on the bottom just offshore of the measurement area, which produced strong onshore-directed turbulence velocities through the measurement volume. On the contrary, suspended sediment particles around the sides and back of the impingement zone were typically carried offshore. Large amounts of suspended sediment were also trapped by counter-rotating vortices behind the down flow. These vortices survived much longer than the down flow and were advected through the measurement volume from onshore to offshore after flow reversal. In most wave cycles, the onshore sediment flux produced by the deflected flow in front of the impingement zone was not high enough to overcome the prevailing offshore advection of sediment. Hence, the net effect of the breaking-wave-induced vortices was to enhance offshore sediment transport. Our experiment was conducted with regular waves and most if not all the breaker vortices generated reached the bottom in the outer surf zone, regardless of whether they impacted inside the measurement area. For irregular wave breaking on a barred beach, Scott et al. (2009) found that the percentage of high sediment concentration events caused by steep

waves and high velocity turbulence events is only a small fraction of the total number of high sediment concentration events (about 1/3 for erosive condition and 1/6 for accretive condition). They attributed the observed low percentages to non-local advection of breaking-wave-turbulence and sediment past the sensors. Our two-phase flow measurements for a mildly erosive wave condition are consistent with their observations.

This study shows that modeling sediment entrainment and transport in breaking waves inherently requires an accurate description of the near-bed flow field associated with the impingement of breaking wave vortices. This study has focused on the overall response of suspended sediment in the measurement volume to the instantaneous flow. An extension of this work will examine the distributions of turbulent flow properties among the sediment particles. For future research, experiments need to be conducted on an erodible bed to determine the boundary conditions for sediment entrainment. Two-phase flow measurements also need to be carried out over a wider range of incident wave conditions and grain sizes to examine the effects of breaker types and structure of breaking-wave-induced vortices on sediment entrainment and transport.

5. Conclusions

The following main conclusions can be drawn from this investigation:

1. The motions of suspended sediment particles and fluid tracers induced by breaking waves on a plane slope were captured simultaneously using a V3V system. The solid and fluid phases were separated based on a combination of particle spot size and brightness in the two-phase flow images. A method was developed to validate the phase separation algorithm and determine the measurement uncertainties in the sediment particle position and velocity. Under still water condition, the sediment position uncertainty was about $\pm 0.1\text{mm}$ and

± 0.5 mm in the direction parallel to the bed and perpendicular to the bed, respectively. The sediment particle velocity uncertainty was about ± 5 cm/s in the “horizontal” direction, and several times larger in the “vertical” direction.

2. The instantaneous velocities of the suspended sediment followed closely the velocities of the surrounding fluid particles in the horizontal direction. The sediment particle velocity in the vertical direction has large measurement uncertainty and was not compared to the fluid velocity.
3. Sediment particles were lifted from the bed and carried into suspension when breaking wave vortices impacted the bottom. The pickup process, during which the sediment particle velocities are upward, lasted for about half a second in a 4-s wave cycle. High suspended sediment load was found in the wall-jet region where the down flow is deflected outward and upward. Measured suspended sediment concentrations correlated well with vertical velocity, turbulent shear stress, and total shear stress in the deflected flow. High correlation coefficient was obtained with the vorticity magnitude when large amounts of sediment were trapped in counter-rotating vortices. Suspended sediment concentrations did not correlate well with turbulent kinetic energy except when counter-rotating vortices were the primary source of turbulent kinetic energy in the flow field.
4. A linear relationship was found between net sediment flux and net turbulent kinetic energy flux over one wave cycle. Net onshore sediment transport was always associated with net positive (onshore) turbulent kinetic energy flux. However, net turbulence energy flux had to exceed a large positive threshold in order to produce net onshore sediment transport. High suspended sediment concentrations were not always found in regions with high turbulence

intensity. Thus, not all the turbulent kinetic energy of the fluid near the bottom was involved in transporting sediment.

5. The velocity distribution created by the impact of breaker vortices on the bottom had an important effect on the net sediment transport over one wave cycle. A strong deflected flow in front of the impingement zone enhanced onshore sediment transport compared to a more symmetrical flow pattern. Suspended sediment particles around the sides and back of the impingement zone were generally carried offshore. Sediment particles trapped by counter-rotating vortices stayed in suspension after the down flow had ceased, and then were transported offshore by the mean flow. In most breaking waves, non-local advection of suspended sediment by predominantly offshore flow velocities produced net offshore sediment transport over one wave cycle.

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Appendix A Scaling Relationship

It is useful to examine how our laboratory conditions scale to field conditions. The laboratory experiment was designed to create suspension-dominated sediment transport in the outer surf zone under plunging waves. Dean's (1973) heuristic model of cross-shore sediment transport suggests that the ratio of sediment fall time to wave period should be kept the same in the model and prototype. For dynamical similitude in the hydrodynamics, flow variables should be

scaled by the Froude number. Hence, the prototype-to-model scale relationships for geometrically undistorted models are (Hughes, 1993):

$$\frac{H_p}{H_m} = \left(\frac{w_p}{w_m} \right)^2, \quad \frac{T_p}{T_m} = \frac{w_p}{w_m} \quad (\text{A1})$$

where H is wave height, T is wave period, w is sediment fall speed and the subscripts p and m denote prototype and model, respectively. For the prototype, we consider a median grain size of 0.3 mm and relative density of 2.65 for quartz sand and a kinematic viscosity of $0.0117 \text{ cm}^2/\text{s}^2$ for saltwater. Using Hallermeier's (1981) empirical formula, we obtain a sediment fall speed of 3.7 cm/s. Fresh water (kinematic viscosity $0.0112 \text{ cm}^2/\text{s}^2$) was used in the laboratory, and the fall speed for a 0.15-mm-diameter sphere with relative density of 2.5 is about 1.5 cm/s. These prototype and model sediment fall speeds yield a value of 6.1 for the prototype-to-model-length-scale ratio and 2.5 for the time-scale ratio. Therefore, the laboratory wave condition ($H_0 = 0.0844 \text{ m}$, $T = 4.0 \text{ s}$) would correspond to a prototype deep-water wave height of 0.51 m and wave period of 10 s. The corresponding wave-height-to-wave-length ratio H_0/L_0 , surf similarity parameters $\sqrt{H_0/L_0}$, and critical H_0/L_0 value for separation of erosive/ accretive beach profiles ($= 1.7\pi w/gT$) in the prototype are 0.0033, 0.44 and 0.002, respectively, which are the same as in the laboratory experiments.

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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Figure 10

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(c)

(d)

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(f)

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