Volumetric Three-component Velocimetry Two-phase Flow Measurements of Sediment Suspension under Regular Plunging Waves

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VOLUMETRIC THREE-COMPONENT VELOCIMETRY TWO-PHASE FLOW
MEASUREMENTS OF SEDIMENT SUSPENSION UNDER REGULAR PLUNGING WAVES

BY
DERYN BECK

A thesis submitted in partial fulfillment of the requirements for the
Master of Science
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VOLUMETRIC THREE-COMPONENT VELOCIMETRY TWO-PHASE FLOW
MEASUREMENTS OF SEDIMENT SUSPENSION UNDER REGULAR PLUNGING
WAVES

DERYN BECK

This thesis is approved as a creditable and independent investigation by a
candidate for the Master of Science degree and is acceptable for meeting the thesis
requirements for this degree. Acceptance of this thesis does not imply that the
conclusions reached by the candidate are necessarily the conclusions of the major
department.

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ABSTRACT

VOLUMETRIC THREE-COMPONENT VELOCIMETRY TWO-PHASE FLOW MEASUREMENTS OF SEDIMENT SUSPENSION UNDER REGULAR PLUNGING WAVES

DERYN BECK

2018

Breaking waves suspend and transport large amounts of sediment particles in the surf zone. Two important aspects of the problem are the mechanism of sediment suspension and the distribution of the suspended sediment. One approach to solving this problem is to measure the sediment particles’ position and movement simultaneously with the characteristics of the flow field. Previous studies have found that sediment suspension events are related to a number of flow parameters including the vertical velocity, vorticity, horizontal velocity, turbulent kinetic energy, total shear stress, and turbulent shear stress. The objective of this study was to design and conduct an experiment that would allow for the gathering of data on the flow field and individual sediment particles simultaneously so the relationship between the characteristics of the flow field and sediment suspension and transport could be understood.

The experiment was performed in a laboratory flume tilted at a slope of 2.5% with a piston type wave maker. Plunging regular waves were generated with a wave height of 0.14 m and a wave period of 3.6 s. Images of the breaking-wave-induced flow field were captured using a Volumetric Three-Component Velocimetry (V3V) system manufactured by TSI Inc. Near neutrally buoyant tracer particles were introduced in the flow to follow
the fluid motion with a diameter of 54 microns and specific gravity of 1.05. The sediment particles were round white glass beads with a diameter that ranged from 0.212 to 0.25 mm and a specific gravity of 2.5. The sediment particles were separated from the tracer particles using the TSI Insight V3V 4G™ program based on the radius, intensity, percent overlap, and search tolerances of the particle images.

Thirty-five tests were conducted. The measured velocity fields were studied and nine representative events were selected and analyzed in detail. The nine cases involve specific breaking-wave-generated flow structures and their interactions with the sediment. The measurements show that vertical velocity, shear stress, and vorticity were all highly related to sediment suspension. The measured data are discussed with the literature on sediment suspension by breaking waves and large-scale organized flow structures generated by other flows.
1. Introduction

1.1 Introduction

A breaking wave, as described by Basco (1985), produces a transition of the underlying flow field from irrotational to rotational motion. The point at which a wave breaks is where the wave height increases to reach a critical level, which results in the collapse of the water onto itself. When this occurs, it can be categorized into several different types of breakers including spilling, plunging, collapsing, and surging. The focus of this study will be on plunging breakers. Plunging breakers are categorized as breaking waves that form a jet that impinges into the oncoming trough. Plunging waves have low wave heights relative to the wavelengths in deep water. These waves are more stable compared to spilling wave prior to breaking; wave breaking occurs spontaneously as the wave crest curls over. Breaking waves result in the suspension and transport of sediment in shallow water or near-shore regions. According to Beach and Sternberg (1996), plunging waves can produce over half of the suspended sediment load in the surf zone.

1.2 Motivation

It is important to understand breaking waves because a significant amount of sediment is suspended and transported as a result of these breakers, particularly in plunging waves. Many studies have been performed to investigate the process of wave breaking and the resulting sediment transport. Various methods have been used to conduct these studies including laboratory experiments, field measurements, and numerical simulations. The experimental studies have utilized a variety of flow measuring instruments including the particle image velocimetry (PIV) and laser Doppler
anemometry (LDA) techniques to measure the fluid velocity field underneath the waves. Nevertheless, there are still many aspects of breaking waves and sediment transport that are not well understood. It is important to understand the mechanism of wave breaking, the resulting flow structures and energy dissipation, and their effects on sediment suspension and transport.

1.3 Objective and Scope

The purpose of this study is to extend the experimental study, performed by LeClaire (2015), to measure the location of suspended sediment simultaneously with the three-dimensional flow structure. A new experimental setup was tested and used to obtain a larger three-dimensional view of the breaking-wave flow field and the resulting sediment suspension and transport. The field of view from the study by LeClaire had a height of approximately 11 mm; for this experiment it was increased to 56 mm. The camera was oriented to give a side view of the wave events. The new orientation decreased the amount of uncertainty in the velocity measurements in the vertical direction. The two-phase flow measurements were recorded and analyzed using Volumetric Three-Component Velocimetry (V3V) technique. The results from the developed experimental procedure gave information on the three-dimensional flow structures of the waves with simultaneous information of the three-dimensional positions of the sediment particles. The measured data were used to obtain both qualitative and quantitative information on the flow parameters related to sediment entrainment and the distribution of suspended sediment. The flow parameters studied include horizontal velocity, vertical velocity, turbulent kinetic energy, shear stress, and vorticity.
1.4 Thesis Layout

The layout of this thesis begins with a literature review to summarize the previous studies related to breaking waves, sediment transport, and the experimental techniques used to capture and analyze these types of events. The experimental setup and procedure follows the literature review. The specific equipment used in the experiment is described including details of the flume and wave maker, types and placement of equipment within the V3V system, size of the sediment and fluid tracer particles, and other information pertinent to understanding the experimental procedure. A significant portion of the experimental method is devoted to describing the phase separation technique used to distinguish between the sediment and tracer particles. After the section on experimental setup, the experimental results are presented. The experimental results focus on the findings in specific cases observed in the experiment. After the experiment results, a section is included on the discussion of the results. The implications of the observed results will be detailed and explained. The final conclusions of the experiment then follow; this will include a summary of the key results and the observed relationships between sediment suspension, sediment transport and the flow parameters. The thesis ends with a section on the suggestions for future work.
2. Literature Review

2.1 Introduction:

Some basic results of the wave breaking process need to be understood in order to address the problem of sediment transport under breaking waves. Breaking waves occur when there is a transition from irrotational motion to rotational motion (Basco 1985). Plunging waves are categorized as breaking waves that form a jet that impinges into the oncoming trough. This impingement creates different large-scale flow structures, which typically includes a vortex. The vortex is created after the impingement of the jet into the trough. The vortex and turbulence created by the breaking wave increase the shear stress and fluid velocities in the bottom boundary layer. Sediment transport under breaking waves has been studied using a variety of methods including laboratory experiments, computer simulations, and data collection in the field. From these studies, researchers have determined that increased sediment suspension is associated with both large bed shear stress and positive (upward) vertical velocity. This literature review summarizes the key results obtained using each of these methods.

2.2 Breaking Waves:

Basco (1985) describes wave breaking as the transition from irrotational fluid motion to rotational motion, which results in the creation of turbulence and vorticity. The point at which a wave breaks is where the wave height increases to reach the critical level which results in the collapse of the water onto itself. Breaking waves can be categorized into several different types of breakers including spilling, plunging, collapsing, and surging. The focus of this study is on plunging breakers. For more information on the characteristics of spilling breakers, the interested reader is referred to Duncan (2001).
Plunging breakers create a vortex of a scale comparable to that of the wave that produces the turbulence. Basco (1985) observed that plunging breakers also induce a second wave motion from the fluid that is pushed upward by the initial wave breaking.

The second induced wave motion described by Basco (1985) was also observed by Jansen (1986). Jansen conducted flow visualization on spilling and plunging waves using UV light and neutrally buoyant fluorescent particles. The study investigated the transformation of each type of wave and the jet splash motions that occur in the breaking waves. Jansen describes the differences in the number and strength and motion of the jet-splash sequences in different types of breakers.

Plunging breakers will occur instead of spilling breakers on a similar beach slope if the wave steepness of the incident waves decreased and the wave period is increased. Plunging breakers can be distinguished from spilling breakers by the formation of a jet in a plunging breaker that impinges on the oncoming trough; the impingement creates a transformation from irrotational to rotational motion. Ting and Kirby (1994) found that plunging breakers produce a net onshore transport of turbulent kinetic energy; spilling waves in contrast have a net offshore transport of turbulent kinetic energy. Their results support the pioneering study performed by Dean (1973) that plunging breakers may produce onshore sediment transport whereas offshore sediment transport is generally observed under spilling breakers. The results from both of these studies show that there is a difference in the structure of turbulence between plunging and spilling breakers.

Aagaard and Jensen (2013) performed experiments to compare sediment transport under plunging waves and spilling waves. The study collected field measurement of near-bed sediment concentrations and analyzed sediment diffusivity in the breaker zone.
and the inner surf zone. Field data were collected on three different natural beaches. The outcome of this research suggested that plunging breakers differ from spilling breakers specifically in the concentration of the sediment suspension and the vertical mixing near the sediment bed. In a spilling surf bore, the measured profile of sediment concentration is concave upward on a log linear plot. In contrast, for plunging waves the measured profile of sediment concentration is linear. The sediment diffusivity in spilling waves was observed to increase almost linearly with distance from the bed; the sediment diffusivity for plunging waves was shown to be vertically constant. These results show that the sediment suspension in spilling waves can be considered a diffusion process, while the vortices of larger breakers typically create vertical mixing through a convective process. The conclusion of the study was that plunging breakers transport sediment landward better than spilling breakers.

2.3 Sediment Transport:

The role plunging breakers play in sediment suspension and transport is important for understanding beach transformation. A study performed by Dean (1973) was one of the first studies to conceptualize suspended sediment movement under breaking waves. Sediment suspension and transport under breaking waves has been the focus of several studies in the recent past. One of the studies, performed by Hsu and Raubenheimer (2006), was performed in the field to compare the field results to numerical results. The outcome of the study showed that the suspension and transport of sediment was a result of shear flow along the bottom boundary layer and turbulence from breaking waves.

In a study performed by Scott et al. (2009), the researchers used a stack of acoustic Doppler velocimeters (ADVs) and fiber-optic backscatter sensors (FOBs) to
collect data on the fluid velocities and sediment concentrations in a large wave flume. The lab setup allowed for the simultaneous collection of different characteristics of the wave event including the occurrence of steep waves, high velocity turbulence events, and sediment concentration. A statistical analysis was performed to determine the correlations between the listed characteristics of the wave events. The study found that the number of steep wave events that resulted in high velocity turbulence and sediment concentration events was only a small proportion of the total amount of steep wave events. The study concluded that most of the sediment transport under breaking waves occurred as a result from events happening adjacent to the measurement area, and that a large amount of the sediment transport resulting from breaking waves was related to advection from non-local sources. The study also included a numerical simulation based on a two-phase flow model for sand transport. The results of the simulation showed that the turbulence from the breaking waves would enhance offshore transport of the sediment.

Sumer et al. (2011) performed two parallel studies on sediment suspension resulting from single plunging breakers. One part of the experiment took direct measurements of bed shear stress on a rigid-bed; the other part of the experiment was conducted with a sediment bed to study morphological changes to the sediment bed and to measure pore water pressures. Their measurements showed a significant increase in bed shear stress directly before and after wave breaking. The study also showed that an upward directed pressure gradient exists in the sediment bed.

Shear stresses were also analyzed in a field study of breaking waves performed by Aagaard and Hughes (2010). The study focused on collecting measurements of the fluid
velocities and suspended sediment concentrations to understand the correlation of turbulence and shear stress with sediment suspension. The analysis showed that the turbulence created from breaking waves could extend to the sediment bed, create large shear stresses, and increase sediment suspension that results in a net onshore transport of sediment in one wave cycle. Aagaard and Hughes show that plunging breakers have a peak in sediment concentrations that is directly related to the onshore velocity maximum. The study also showed that the bed shear stress in plunging breakers is one order of magnitude higher than in surf bores and several orders higher than in shoaling waves. By separating the instantaneous vertical sediment flux into those from the local breaker vortices and those from the small-scale turbulence, the results showed that the vertical sediment flux resulting from local breaker vortices was strongly related to the vertical velocity variance. The study concluded that the plunging breakers result in the mobilization and upward mixing of sediment.

2.4 Vortex Motions:

Breaking waves are complicated events. In order to simplify the event, several studies have focused their research on sediment suspension caused by specific flow structures that may also be observed within a breaking wave. A study performed by Sutherland (1967) was one of the first studies to focus on the relationship between a coherent structure, in his case a vortex ring, and particle suspension. Sutherland found that the impact of the vortex ring onto the sediment layer results in an increase in local shear throughout the sediment bed. The movement of these particles, including suspension, depended on the submerged weight of the particles and the amount of their volume that was exposed.
A study performed by Munro et al. (2009) focused on particle suspension resulting from vortex rings. In their study, Munro et al. (2009) described the advantages of using vortex rings by stating that vortex rings are one of the simplest vortex structures and they can be easily and consistently reproduced in an experiment. Munro et al. used PIV techniques, high-speed video, and a light attenuation method to observe the propagation of vortex rings and the resulting sediment displacement. The study has produced several conclusions. They described that for small sediments, the lift force resulting from the shear will not affect the particles after they have risen a vertical distance comparable to the boundary-layer thickness. The conclusion from this is that once the sediment is past that point, any additional rise is a result of the particles’ inertia and the vertical component of the fluid velocity. The quantitative results from the experiment were analyzed in terms of the Shields parameter, \( \theta = U^2/\gamma gd \), where \( U \) is the vortex propagation speed. The critical conditions to be met in order to induce suspension \( (\theta/\theta_c \geq 1) \), were examined as a function of the particle Reynolds number and the dimensionless particle size, \( d/\delta \) where \( d \) is the diameter of the particle and \( \delta \) is the thickness of the viscous sublayer. They noted that the viscous stresses decrease the hydrodynamic lift and drag forces resulting from the vortex flow field acting on what they consider to be as the near-surface sediment grains. This observation is consistent with the “hydrodynamic roughness” limit that has been suggested by other researchers.

Another study by Munro (2012) was performed focusing on a sloped sediment bed and scenarios where the suspension is observed under critical conditions where the sediment is just induced into motion. Similar to his previous study on a horizontal bed the sediment motion was analyzed in terms of the Shields parameter. The focus of the
experiment was to observe the effect of increasing the slope of the sediment bed. The results show that there is a significant influence of the bed slope on the suspension of the particles; the effect of the additional down sloping gravitational force was credited for this influence. Another result from this study focused on the measured critical Shield parameter using the propagation speed of the vortex as the characteristic velocity in the traditional Shields parameter. Though the magnitudes are different there existed similar trends between the two parameters showing some validity to using the propagation speed of the vortex as the representative velocity in the Shields parameter.

Another continuation from the Munro et al. (2009) study was by Bethke and Dalziel (2012) who focused on erosion resulting from vortex rings. The study used similar techniques as Munro et al., namely PIV, for analyzing the flow dynamics and the light attenuation method to measure bed erosion. The suspension of several different particle sizes under a symmetrical vortex ring were investigated; the suspension pattern or crater created from the vortex was also evaluated. The results showed the effect that bed permeability had on sediment suspension; the study focused on the slip velocity at the sediment bed and the flow within the sediment bed. Bethke and Dalziel (2012) concluded that the particle diameter and permeability of the particle bed has a significant effect on the crater formed by the suspension from the vortex ring. The conclusions were that as the sediment particle size increased, the crater depth increased and the crater radius decreased. This pattern is thought to be caused from the differing critical Shields parameters and the permeability of the sediment bed.

An experimental study on brownout created by rotorcraft was conducted by Johnson (2009). The goal of the study was to understand sediment entrainment and
transport that result from rotorcraft that produces a visual hindrance to the pilots and physical damage to the rotorcrafts. Though the project is significantly different from the subject of this paper, several similarities exist in the sediment movement under breaking waves and sediment movement under rotorcraft. The study by Johnson used PIV technology to study the sediment motion resulting from the vortices created by rotorcraft. The results of the study show that the sediment suspended from two different causes, the forces from the rotor flow and from the bombardment of other particles. The ground wash velocities and amount of bed erosion was highest in the areas that the vortices impacted the ground; the conclusion was that the wall shear increased as a result of the additional velocities produced by the wake vortices. Johnson argued that sediment suspension occurs when the vertical drag on the particle exceeds the particles immersed weight. The vertical drag results from the vertical velocity created primarily by the turbulent eddies.

2.5 Numerical Studies:

Several researchers have used Large Eddy Simulation (LES) schemes to model sediment suspension by breaking waves. Zhou et al. (2017) performed a study to analyze the interaction between turbulent structures and the transport of suspended sediment. A key finding was that more than half of the suspended sediment occurred as a result of coherent structures; though suspension events occurring under coherent structures accounts for less than one tenth of the total number of events.

Suzuki, Okayasu, and Shibayama (2007) performed a numerical simulation to model the sediment concentration under breaking waves. This simulation was performed in conjunction with a laboratory experiment to validate the results of the simulation.
They found that the computed sediment concentrations were about 1.5 times greater than the measured values; however, the general patterns and conclusions agreed between the simulation and the experiment.

Naqavi and Piomelli (2010) performed a LES study on the interaction of spanwise vortices with a boundary layer. The vortices are introduced at the boundary layer by a forcing term in the governing equations. The vortices are then advected by the flow and interact with the boundary layer. The focus of the study was to investigate the system as it returns to equilibrium. The spanwise vortices simulated in this study are similar to the spanwise vortices resulting from breaking waves. One conclusion was that the turbulence from the near-wall eddies increase the wall shear stress.

Pederson et al. (1995) developed a 2D simulation to model the transport of sediment suspended in plunging breakers. The plunging breaker was modeled by superimposing a jet on a nonbreaking wave. The sediment suspension and transport is described by a Lagrangian description. The suspension of the sediment in the boundary layer is described by a diffusion process; the transport of the sediment is described by convection based on the flow field. The transport model is based on the relationship between the dimensionless bed load and the Shields parameter. The results from the simulation were compared with a laboratory experiment performed by Dette and Uliczka (1986); the comparison showed similarities with regards to the order of magnitude of the concentration levels and the cross-shore distribution.

2.6 Studies on Plunging Waves:

A study performed by Nadaoka, et al. (1989) described breaking waves by focusing on the large scale eddies resulting from the breaking waves. They obtained the measured
fluid velocities by using a two-component fiber-optic laser-Doppler anemometer (LDA) and used the results to develop a qualitative description of the flow structure based on the entrained air bubbles. Nadaoka et al. (1989) found that there exists large-scale eddies that they refer to as “horizontal eddies” and “obliquely descending eddies”. They observed that these eddies are created by the wave breaking process and then left behind the wave crest. They show that these eddies result in the production of Reynolds stress in the upper layer of water, and as a result affect the deformation of the mean flow field. The study also shows that the formation of the eddies brings a large amount of vorticity into the initially irrotational flow. The researchers were able to separate the flow field into two components: the “wave motion” and “eddying motion” together with turbulence. They found that the generation of the mean rotational velocity component resulting from the wave breaking causes an increase in the mass and momentum transport in these waves.

A study by Ting and Kirby (1994) also used LDA to obtain velocity measurements under plunging and spilling waves to develop a quantitative description of undertow and turbulence in the surf zone. They measured wave decay and set-up by using a capacitance wave gauge. The LDA and wave gauge measurements were used to study the characteristics of mean flow and turbulence to compare the flow characteristics in spilling and plunging breaking waves. Their study was motivated by the work of Dean (1973) and sought to determine the relationship between mean flow and turbulence. They found that the vertical variation of undertow and turbulence intensity are much smaller in plunging breakers compared with spilling breakers. The study also found that the turbulent kinetic energy produced by the breaking waves was transported seaward under spilling breakers and landward under plunging breaker. If it is assumed that
turbulence in the water column keeps sediment in suspension, the results suggest that there is a direct relationship between turbulence transport and sediment transport. The results indicated that the differences that exist between plunging and spilling waves are related to the processes of wave breaking and the rate of turbulence production.

Ting and Kirby performed another study in 1995 using the same setup. The study examined the role of turbulence by applying the transport equation for turbulent kinetic energy (the k-equation). The results of the study show that large-scale motions under plunging breakers control the turbulence; the transport of the turbulence in the inner surf zone differs based on the wave condition and types of breakers. The study also showed that the turbulence production and viscous dissipation that occurred below the trough level only accounted for a small amount of the loss of wave energy resulting from wave breaking.

Otsuka et al. (2017) performed a study by observing breaking waves in a flume with a 1/20 sloped beach and a sandpit covering the surf zone. The sediment concentration, fluid velocity, and surface elevation were measured at 100 mm intervals cross-shore over the surf zone. The concentration of suspended sediment was measured using an optical concentration sensor at vertical intervals of 10 mm from the bottom to the wave trough. The fluid velocity was measured using PIV with fluorescent tracer particles. Three types of waves were analyzed including two cases of plunging breakers and one of a spilling breaker all with different wave characteristics. The experimental conditions were also modeled using the LES model outlined in Watanabe et al. (2005). The flow structures resulting from the computational model are considerably more complex than most models have predicted and involves the generation of organized
vortices. Their model predicts that obliquely descending eddies resulting from adjacent primary vortices produce transverse convergent near-bed flows. The near-bed flows deposit sediment that is then ejected upward between the vortices. This model, though considerably different from many other models proposed, provides a good prediction of sediment concentration profile resulting from plunging waves.

2.7 Studies Applying PIV Technology:

In contrast to LDA which can only be used to measure fluid velocity one point at a time, the particle image velocimetry (PIV) technique can provide instantaneous full flow field measurement in a 2D plane (planar PIV) or in a 3D volume (3D or volumetric PIV). In a study performed by Kiger and Pan (2000) the researchers performed a series of experiments to develop a procedure to measure two-phase solid-liquid flows using PIV. The study is particularly relevant to turbulent flows containing sediment; this type of flow is common and applicable to most applications in the natural world, including sediment suspension from breaking waves. A study performed by Kiger et al. (2014) and a study performed by Johnson et al (2009) applied similar techniques to particle tracking suspended under rotorcraft operations. These studies are useful in understanding the shedding of vortices and tracking particles within those vortices.

Ting (2006) applied PIV to study the turbulence resulting from solitary spilling waves. The study also used acoustic Doppler velocimeter (ADV) to obtain the three components of water velocity at various vertical locations. The measurements obtained were used to compute the ensemble-averaged velocities. The ensemble average subtraction was used to determine the turbulent velocity fluctuations, turbulent kinetic energy, and Reynolds stresses. The results showed that the structure of turbulence
resulting from the breaking wave changed throughout its movement from the free surface to the bottom; the change correlated to the transition from 2D to 3D structures. The analysis showed that these structures produced most of the turbulent shear stress and kinetic energy. The study concluded that these structures transported turbulence energy and fluid momentum from the free surface to the bottom boundary.

Ting (2008) is a continuation of the previous study using the same equipment and procedure. The focus of the study was to study the evolution of large-scale turbulence structures. The results of the study showed that the flow structure created by a solitary breaking wave formed two counter-rotating vortices attached to a downburst. Ting (2008) studied the temporal correlation between turbulent kinetic energy and shear stress with breaking waves. The results showed that significant variation in turbulent kinetic energy and shear stress for each case. Ting (2008) discussed that these differences are from the variation in the structure of the large eddies that he observed at the vertical mid-point and the bottom.

Ting and Nelson (2010) applied PIV techniques to study the large-scale turbulent flow structures resulting from spilling waves. The study focused on the near-bed structures by using a horizontal measurement plane approximately one millimeter from the bottom of the flume. The results from the experiment indicated that the large-scale turbulence descended to the bottom as a downburst of turbulent fluid and produced large turbulent shear stress. The study was continued in Ting (2013) using plunging regular waves. The results from this study showed that the vortices resulting from the plunging wave impacted the bottom at the approximate instant of maximum positive wave-induced velocity. Ting noted that the vortex resulting from the plunging breaker formed a 3D
vortex loop as it descended to the bottom of the flume. The analysis of the turbulent velocity fields showed that the shear stress resulting from the plunging waves would exceed the critical shear stress needed for the initiation of sediment motion in a sediment bed.

2.8 Studies Applying V3V Technology:

The volumetric three-component velocimetry (V3V) technique (Lai et al., 2008) allows users to track the movements of fluid tracers in a three-dimensional space. The principles of data processing performed using V3V is described thoroughly by the authors. The authors also presented several examples of applications of the V3V technique.

Kitzhofer et al. (2011) described different methods that can be applied to conduct 3D flow measurements including V3V software, holographic PIV, tomographic PIV, and defocusing PIV. The study describes the different aspects to consider for 3D flow measurements including data generation, filtering, visualization mapping, rendering, and display. Ting et al. (2013) applied the results from Lai et al (2008) and applied V3V software to collect measurements under breaking waves. Ting et al. (2013) was able to apply V3V technology to construct 3D vortices resulting from breaking waves. Prior to this development, these structures were analyzed using PIV; this form of analysis only produced 2D views of the structures on various planes.

Ting and Reimnitz (2015) conducted a lab study applying V3V software to measure three components of water velocity in 3D space. The measured water velocities were analyzed to compose the structure of the breaker vortices. The results of the analysis allowed the composed structure to be observed throughout the measurement
volume. The study showed the ability of applying V3V software to measure the water velocity, and the capacity of simultaneous measurements of the sediment particles suspended and transported within the flow. The study, however, did not provide any measurements of individual sediment positions and velocities within the breaking waves.

A study performed by LeClaire and Ting (2017) used V3V software to simultaneously measure tracer and sediment particles in breaking waves. The study used the same tilting flume as the one used for the experiment described in this paper. For the study performed by LeClaire and Ting, the camera was setup to view the flow field in the outer surf zone through the bottom of the flume. This allowed for higher measurement accuracy in the horizontal directions (X and Y). The field of view for this experiment was restricted to the region adjacent to the bottom of the flume; the measurement volume was calibrated from near the bottom of the flume up to a height of 12 mm above the bottom. The tracer particles and sediment particles were separated based on a combination of particle spot size and brightness in the captured images. The two types of particles (solid particles and fluid tracers) were used to study the correlations between suspended sediment concentration and various flow parameters, and to correlate the suspended sediment flux and turbulent kinetic energy flux. The results of the study show that sediment particles were primarily lifted by breaker vortices impinging on the bottom. Despite the high turbulent kinetic energy, the observed suspended sediment concentrations were small in the impingement zone where the water velocities were downward. The results of data analysis showed a strong relationship between the suspended sediment concentration and the vertical velocity and shear stresses in the
deflected flow. A relationship was also found between the suspended sediment concentration and the vorticity magnitude in the counter-clockwise vortices.
3. Experimental Setup

The experiment was conducted in a tilting flume with a length of 25 m, a depth of 0.75 m, and a width of 0.9 m. A piston type wave generator was used to produce regular waves (Stokes 2nd order waves) with a height of 0.14 m with a wave period of 3.6 s. For this experiment, the water depth at the wave maker was set as 0.4 m. The flume was set at a slope of 1:40 (2.5%). Figure 3.1 shows the layout of the flume and wave maker.

Figure 3.1 Tilting flume with a piston type wave maker used for the experiment
The water and sediment particle positions in a three-dimensional measurement volume were recorded using a volumetric three-component velocimetry (V3V) system manufactured by TSI Inc. This system has three main components: the camera, laser, and synchronizer. The camera used for this system was a PowerView 4MP-180. The laser used was a YAG Evergreen (145.200)-15 BSL equipped with two cylindrical lenses with focal lengths of 50 mm and 100 mm. The camera and laser were controlled by a 610036 Laserpulse Synchronizer. Figure 3.2 shows each component of the V3V system. To synchronize the different experiment runs, the V3V system and the wave generator were externally triggered by a TTL (transistor-transistor Logic) signal from a personal computer.

The V3V system was located onshore from the wave generator where the water depth was approximately 0.20 m. The camera was mounted in an upright position so that the bottom of the flume was within the camera’s field of view. The vertical position of the camera was determined by a procedure that will be described in Section 3.1. A false bottom was created from two layers of ceramic tiles. The top layer of tiles was covered with sandpaper to create a rough surface. The average surface particle roughness of the sandpaper was 0.265 to 0.269 mm. The total thickness of the false bottom was approximately 25 mm.
Figure 3.2 V3V equipment used for experiment; PowerView 4MP-180 camera (top left), YAG Evergreen (145.200)-15 BSL laser (top right), 610036 Laserpulse Synchronizer (bottom).
The experiment included 35 tests. Each test started from still water condition, with approximately 20 minutes of inactivity between the mixing of the particles and the beginning of a test. The first two tests contained only tracer particles; all the proceeding tests (Test 3-35) contained both tracer and sediment particles. A few of the tests contained images that were blurred due to problems with the hardware. Portions of these tests could not be processed, so some tests in effect did not contain images for the full test set. Apart from these few exceptions, the typical test sequence recorded 400 frames at a sampling frequency of 15 Hz.

Preliminary experiments were conducted to optimize the horizontal distance between the flume sidewall and the camera; these experiments were performed to find the position of the camera that would produce a field of view that could record the most turbulence events while minimizing sidewall effects and visual blockage from air bubbles in the breaking waves. The field of view of the V3V camera was located in the outer surf zone after the waves have broken so that the suspension of the sediment could be observed by the camera. The camera was positioned 400 mm in front of the flume sidewall. Figure 3.3 shows the unobstructed vertical viewing angles of the three cameras along with the projected false bottom. The sidewall is represented by the Y-axis at X=0; the camera was placed 400 mm to the left of the sidewall, and the field of view was 230-350 mm to the right of the sidewall. The vertical view from the top camera corresponds to the area between the solid lines and the left and right view corresponds to the area between the dashed lines. The lines were created from a linear least-square-fit of the measured elevations of the upper and lower boundaries of the camera line of sight at intervals of 100 mm across the flume (see Section 3.1).
Figure 3.3 Measurements for field of view taken with the camera located 400 mm from the sidewall

The laser was mounted underneath the flume to project the laser beam upward through the bottom of the flume. Two mirrors were situated to reflect the laser beam. The first mirror received the vertical beam from the laser and reflected it offshore parallel with the bottom of the flume through the field of view of the camera. A second mirror located approximately 2 m offshore from the first mirror was situated to reflect a large portion of the beam back onshore through the field of view to increase the laser light intensity in the measurement volume. Figure 3.4 shows the layout of the camera, laser, and mirrors. The laser position and mirror angles were adjusted so that the light sheet produced by the laser would cover the entire measurement volume shown in Figure 3.3.
Figure 3.4 V3V measurement layout

3.1 Camera Position

Breaking waves are complex phenomena and require several things to work simultaneously to capture the events correctly. The waves typically contain complex 3D flow structures, strong sediment suspensions, and at times can contain large amounts of air bubbles that can obscure the view of the camera and the path of the laser. The depth of the field of view of the camera for this experiment was calibrated to approximately 120 mm. The width of the flume was 900 mm. This means that the camera captures only about 13% of the width of the flume. Several measurements and calibrations were performed to find an optimal placement of the camera so that the field of view would be in an area that would capture the largest amount of events while minimizing the
interference of air bubbles and sidewall effects. The camera was placed at varying
distances from the sidewall; adjustment was also made to optimize the vertical position of
the camera. The height and period of the incident waves were chosen so that the waves
broke a short distance offshore of the measurement volume.

The distance between the camera and the sidewall affected the distance between
the sidewall and the field of view within the flume. Bubbles obscured the field of view
more frequently as the field of view was moved deeper into the flume away from the
camera. The measurement volume should be positioned at least one still water depth
(about 0.2 m) from the sidewall to minimize the side wall effects. The reference plane
represents the farthest point of the measurement volume. The measurement volume is the
intersection of the laser illuminated region and the camera viewing region.

The laser head for the V3V system was placed under the flume onshore of the
field of view. A mirror angled at 45 degrees was mounted on the flume floor to reflect
the vertical light from the laser horizontally, parallel with the slope of the flume, through
the field of view. As the laser-illuminated region expands down the flume, the light
intensity decreases with distance. A mirror was placed just offshore of the field of view
to reflect the light back down through the camera’s field of view. The light intensity of
the particles increased significantly by adding the extra mirror, but there were still
limitations to the intensity of the light sheet and power of the laser. The camera also had
limitations because of the small size of the particles; the camera could not focus on the
particles throughout the width of the flume. Both of these limitations from the laser and
the camera limited the depth of the field of view to approximately 120 mm.
To determine the placement of the camera, the camera was placed at varying distances from the sidewall. The upper and lower boundaries of the line of sight of each sensor were measured by placing a steel ruler vertically within the flume at varying distances from the sidewall. After the measurements were taken, the camera was then calibrated to locate the reference plane. The information from these tests were compiled to find an optimal placement of the camera.

The first position of the camera was at a distance of 300 mm from the sidewall. Figure 3.5 shows the field of view for that camera placement. The figure shows that the field of view of this camera placement would be approximately centered in the flume. Problems with this placement include area being cut off from the top and bottom due to the upper boundaries of the field of view of the left and right camera, and the lower boundary of the top camera. Thus, a significant portion of the bottom area would not be captured with this camera placement. Calculations were performed to determine the approximate location of the field of view if the camera was lowered by 25 mm. Figure 3.6 shows the field of view for this position. The figure shows that the false bottom would no longer be excluded from the view of the top camera. However, the distance between the sidewall and the field of view was deemed too large for measuring an aerated flow.
Figure 3.5 Field of view from the camera at 300 mm from the sidewall.

Figure 3.6 Field of view from the camera at 300 mm from the sidewall and a lower vertical position of 25 mm.
The second position observed was placing the camera at a distance of 350 mm from the sidewall. Figure 3.7 shows the field of view that was observed from the results of that test. Figure 3.8 shows the estimated field of view that would be observed by lowering the camera by 25 mm. Some of the same issues were observed in these situations that occurred in the previous camera position. The main issues were that the field of view was still too far from the sidewall and too much of the field of view of the bottom cameras was not being used.

![Figure 3.7 Field of view from the camera at 350 mm from the sidewall.](image)
Figure 3.8 Field of view from the camera at 350 mm from the sidewall and a lower vertical position of 25 mm.

The third position of the camera was at a distance of 400 mm from the sidewall. Figure 3.9 shows the resulting field of view from this camera placement, and Figure 3.10 shows the field of view if the camera was lowered by 25 mm. The observations from this placement were that the field of view is closer, centered at approximately one third of the distance into the flume. This would be where most of the breaking wave events can be observed without the view being obscured frequently by air bubbles. Figure 3.10 shows that the bottom cameras will still have portion of their field of view obscured by the false bottom, but that the field of view does include the bottom where the sediment suspension will be observed.
Figure 3.9 Field of view from the camera at 400 mm from the sidewall.

Figure 3.10 Field of view from the camera at 400 mm from the sidewall and a lower vertical position of 25 mm.
The fourth and fifth placements of the camera were at distances of 450 and 500 mm from the sidewall, respectively. The fields of view for both of these instances were too close to the sidewall. At these locations, the camera would have less interference from air bubbles, but it would also not capture a large amount of the breaking wave events and would experience interference from the sidewall. Figure 3.11 shows the field of view that would occur from a camera placed at 450 mm from the sidewall and lowered by 25 mm. Figure 3.12 shows the field of view that would occur from a camera placed at 500 mm from the sidewall and lowered by 25 mm.

Figure 3.11 Field of view from the camera at 450 mm from the sidewall and a lower vertical position of 25 mm.
3.2 Tracer and Sediment Size

Two types of particles, fluid tracers and solid particles were used in the two-phase flow measurements to study the fluid motion and sediment motion. Several preliminary experiments were conducted to find tracer particles that could accurately be recorded by the V3V system. The first factor taken into account for these experiments was the ability of the particles to reflect a sufficient amount of the laser light to be detected by the V3V camera. Tracer particles with diameter less than 50 microns were found to be too dim, which resulted in a poor particle detection. White hollow glass spheres with a mean diameter of 54 microns were used as tracer particles to represent the fluid; the particles had a specific gravity of 1.05.

The size of the sediment particles used was decided based from the size of the tracer particles. The most crucial aspect of picking a sediment particle size was finding a
size that could be separated from the tracer particles. Other factors considered when choosing a sediment size included being able to focus on the sediment particles simultaneously with the tracer particles, limitations with available sediment sizes, and finding a sediment size that could represent sediment on a beach when scaled. Several additional experiments were performed to find an appropriate sediment size. The size of the sediment particles after taking into account the afore-mentioned aspects and the results from the previous tests were chosen as 0.212 to 0.25 mm round white glass beads with a specific gravity of 2.5. The sediment particles were mixed in the flume and allowed to settle to the bottom before each test; a sediment bed was not used in this experiment. Figure 3.13 shows a raw image with both types of particles and the size differences between the particles can also be seen.

Figure 3.13 Raw image of frame 2674 showing sediment and tracer particles
3.3 Camera Calibration and Image Processing

Studies containing detailed explanations of V3V software include Pereira et al. (2000), Troolin and Longmire (2009), and Sharp et al. (2010). The camera probe used for this experiment had three apertures set up in the shape of an equilateral triangle. The images captured by the camera were processed in four separate steps for the flow field and in two separate steps for the sediment positions. The processing steps for both cases were performed in the same order, but by changing the settings of the image processing parameters. The specific settings and procedures used in each case are explained in the following paragraphs and in section 3.5.

The first step of the image processing is particle identification in two dimensions. Each V3V capture includes a total of six images. The first frame, frame A, includes three images one from each of the three camera apertures. The second frame, frame B, includes three images taken in the same way. The parameter settings used in the particle identification include minimum intensity threshold, minimum radius, maximum radius, and percent overlap.

The second step is to identify the particle positions in three dimensions. In this step, the 2D particles from all three of the images in each frame are used to search for particle triplets. The step is done twice for each frame. Each of the three camera sensors view the measurement volume from a unique angle. The different angles allow the particles to be captured from three slightly different directions, which can be combined to determine the three-dimensional position of the particles. Figure 3.14 shows a schematic of the V3V aperture arrangement from Ting et al. (2013). Each camera in the schematic is represented by a cylinder with a line representing the line of sight from the camera to
the particle represented as a grey sphere. The white square next to each of the cameras represents the two-dimensional view captured by the specific camera. For example, the top camera has a blue line that represents the line of sight from the camera to the particle. In the corresponding white square, the blue line is shown as a blue dot and the green and red lines represent the line of sight of the left and right cameras, respectively. The software searches along the rays to detect possible particle matches.

![Diagram of three cameras and particle](image)

**Figure 3.14 Layout of the three apertures on the camera all capturing the position of a tracer particle represented by a grey sphere. The two-dimensional representation of the sight lines of all three cameras is shown in the white boxes next to each of the cameras (from Ting et al. 2013)**

The triplet search performed in each frame is done in two steps. The first step is for the coarse search. The coarse search looks for matching particles in each frame within the coarse search tolerance. After the coarse search, a fine search is performed, which necessitates a particle position in all three frames to match within the set fine search tolerance. The two-dimensional particle is not detected as a three-dimensional
particle if a triplet pattern for the particle cannot be found within the tolerances. The triplet pattern is applied to all two-dimensional particles detected in the two-dimensional particle identification stage.

The camera was calibrated prior to the image capture to get accurate locations of the detected particles. A backlit target with a grid pattern was used for the calibration. Each dot on the grid was 5 mm apart. The target began at the far end of the calibration region, 782 mm away from the camera. A stepping motor was used to traverse the target at 2 mm increments from the back to the front of the calibration. The target used for the calibration is shown in Figure 3.15 and the traverse that moved the target forward is shown in Figure 3.16. The images taken of the target at each 2 mm interval were processed to find the triplet patterns throughout the calibration region. Dewarping polynomials were also found which show how the triplet pattern changes throughout a calibration plane due to perspective distortion. The results from the calibration are shown in Figure 3.17. The dewarping errors are shown in the bottom left plot. The triangles on the right side of the figure represent the signature triplet pattern created using the calibration target at each interval in the calibration process. The smallest triangle represents the image taken at 782 mm from the camera, and the largest triangle corresponds to the image taken 662 mm away from the camera.
Figure 3.15 Target used for calibration

Figure 3.16 Traverse with target attached, used to move the target at specific and accurate intervals
In the third step, the three-dimensional particles in each frame are processed to determine velocity vectors. The particle tracking is based on a statistical process from Ohmi and Li (2000) called the Relaxation method. The purpose of this process is to match particles from Frame A to Frame B. For this processing step, the three-dimensional particles detected in the second step are divided into clusters depending on their locations. The hypotheticals pairs of particles between frames A and B within the clusters are given a probability representing the likeliness of being a true match. The initial probability is the same for each hypothetical pair. The assumption is that the particles within the same area will move in a similar manner. The probabilities of the matches are iterated for each particle in the cluster until the probabilities converge. The process considers how all the particles in the cluster are matched to determine if a
suggested match is acceptable. In other words, given that most particles within a cluster will move in a similar manner then the suggested matched pairs between frame A and B will show a similar directional movement in most of the individual pairs. This suggested matching represented by the similar movement in each pair would result in the highest number of pairs within the cluster.

The fourth and final processing step is to use the velocity vectors from the third step to create a velocity field. The randomly spaced velocity vectors determined in the third step within a set area are interpolated onto a rectangular grid. For this experiment, the interpolation was performed at 8 mm spacing with 50% overlap so the grid resolution is 4 mm. The grid allows the determination of other parameters such as turbulent kinetic energy and vorticity to be calculated at each grid point throughout the measurement volume. These calculations were performed and plotted with Tecplot 360 software.

3.4 Particle Separation

The raw images for each test were processed based on several parameters including maximum radius, minimum radius, intensity threshold, percent overlap, and coarse and fine search tolerance. Each of the afore-mentioned parameters affects the processed results differently. The maximum radius, minimum radius, intensity threshold, and percent overlap were the parameters used for the 2D particle processing (p2d); the coarse and fine search tolerances were used for the triplet processing (p3d).

The minimum and maximum radii are used to distinguish particles from the background, and to help determine the center location of the particles. The first step in the image processing process is to apply the maximum radius throughout each frame for pixels greater than the intensity threshold. A support radius, which is determined by the
maximum radius, is applied to each pixel in the frame. In order to be considered as a candidate for a particle a few things have to be true: the current pixel’s intensity has to be greater than the intensity established threshold parameter, and the current pixel’s intensity has to be greater than the intensities throughout the support radius.

The theoretical size for all of the particle candidates discussed is calculated based on what is called an R-value. For all the detected particle candidates, the difference is taken between the maximum intensity within the support radius (the center pixel set by the maximum radius) compared with the intensity of all the other pixels within the support radius. This difference is applied to a local counter. After sampling all supporting pixels, the counter must be such that R is greater than the minimum particle radius. The R-value is equal to the square root of the quantity of the ratio of the counter over $\pi \left( R = \sqrt{\text{Counter}/\pi} \right)$. The criteria of the program is that for the candidate to be considered a particle the R-value has to be greater than the minimum radius.

After the R-value is determined, a Gaussian function is applied to all particle candidates. The Gaussian function determines the particle radius in the X and Y direction and the center location of the particle. This step also filters out the candidates that do not have a support radius that has a Gaussian fit.

The overlap percentage can be applied so that more than one particle may be identified within the support radius. The overlap percentage determines a distance dependent on a set percentage of the maximum radius and the size of the particle. When the support radius is applied to a local intensity peak in the first series of particle processing steps, more than one intensity peak may be present within the same support...
radius. The parameter allows an intensity peak to be detected as a valid particle even if it is not the highest intensity peak within its support radius. The overlap percentage parameter allows more than one local peak to be processed as a detected particle with overlapping support radii. When a given intensity peak has a neighboring intensity peak within the support radius that is greater than the intensity threshold parameter, then in order to be considered as a candidate for a particle, the location of the neighboring peak must be a distance away from the location of the original intensity peak. This distance has to be either equal to or larger than the distance determined by the overlap percentage parameter.

After the 2D particles (p2d) are identified, the 3D particles (p3d) are determined by combining the locations of the 2D particles from each of the corresponding images of the three cameras. A triplet match (3D particle) occurs when the same particle is detected in each of the cameras. This only occurs when a triplet of 2D particles from the corresponding images of all three cameras (top, right, and left) falls within the tolerances set by the search triangle defined by calibration graph in Figure 3.17. The number of matched particles increases as the search tolerances are relaxed, but the uncertainty in the 3D locations of the particles also increases as the tolerances are relaxed.

### 3.4.1 Water Particle Velocity

Two types of particles were used in the experiment: tracer particles to represent the movement of the water, and sediment particles. The tracer particles were polystyrene latex spheres with a mean diameter of 54 µm and a specific gravity of 1.05. The sediment particles were white solid glass spheres with a size range of 0.212 to 0.25 mm and a specific gravity of 2.5. The water particle velocity was determined based off the
velocity of both the tracer and sediment particles. The processing parameters in Insight are designed for finding tracer particles; because two types of particles are used in the experiment, tracer and sediment, the parameters were adjusted within Insight to filter out particles smaller than certain sizes when only the sediment particles were meant to be detected. The processing parameters in Insight allow the filtering of particles smaller than a specified intensity or radius, but the program does not have parameters that remove particles larger than a specified size or intensity. This allowed the detected sediment particles to be extracted by filtering out the significantly smaller tracer particles, but the Insight program is not capable of the filtering of larger particles while including only the tracer particles. Therefore, the water velocity vectors were determined based on the motion of both tracer and sediment particles.

In LeClaire and Ting (2017), the image processing parameters in Insight were not used to separate the sediment and tracer particles. A different set of filters were created in Matlab to separate the two types of particles based on a combination of spot size and brightness of the particles identified in the 2D images. The PowerView Plus 4MP cameras used by LeClaire and Ting (2017) have an intensity dynamic range of 12 bits, whereas the 4MP-180 cameras used in this study have an intensity dynamic range of only 8 bits. This difference in the camera intensity dynamic range necessitated a different approach for particle separation. The camera used in this experiment had a much smaller pixel intensity range that did not allow for clean separation between the two types of particles based on a simple relationship of particle spot size and brightness.

The phase separation scheme used in this study can only remove the tracer particles. Consequently, all the identified particles (sediment and tracers) have to be used
to re-construct the fluid velocity field. Furthermore, due to the high concentration of suspended sediment in some captured images, it is not feasible to remove the large particles and use just the remaining tracers to determine the fluid velocities; the seeding density would be too low. However, this did not significantly skew the measured velocity field. The sediment particles have a much higher fall velocity so that their concentrations are low in the upper part of the measurement volume. The sediment particles that have been suspended into the measurement volume would have similar horizontal velocities as the velocity of the water and the tracer particles. In the flow regions where the sediment concentrations are low, the velocities determined should represent the fluid velocities. In regions where the sediment concentrations are very high (e.g., in a dense sediment cloud), the measured velocity might be more indicative of the sediment velocity.

The processing parameters used to process the particles for the velocity field had an intensity threshold of 10, a minimum radius of 1 pixel, a maximum radius of 2 pixel, a percent overlap of 50%, a fine search tolerance of 0.5 pixel, and a coarse search tolerance of 1 pixel. These parameters were set to filter out the background noise and particles that are poorly focused.

A Still Water test was performed by taking images after letting the water remain still for 20 minutes after a wave event. After 20 minutes, all the sediment particles should have fallen to the floor of the flume, and all the tracer particles should have little to no velocity in any direction except for a small fall velocity. The images taken from the still water test were processed to produce the tracer particle velocity in each direction, which may be considered the measurement uncertainty of the V3V system. The absolute
velocity based on the 400 still image water frames has a mean value of 4 mm/s in the X and Y direction and 3 cm/s in the Z direction. In the V3V coordinate system, the +X direction is offshore, the +Y direction is upward, and the +Z direction is towards the V3V camera.

3.4.2 Sediment Particles

The sediment particles were processed based on the parameters previously discussed with the goal of filtering out the tracer particles and the background noise. Each parameter was studied and adjusted so that the optimal setting could be found that would filter out the most tracer particles and accurately detect the highest amount of sediment particles.

Several preliminary experiments were performed prior to the actual experiment. Each preliminary experiment was labeled as a lesson and focused on a specific issue of the overall lab procedure. Lesson 27 was performed using the same equipment layout and sediment sizes as the actual experiment, Lesson 30. Lesson 27 was performed to select the values of the image processing parameters for phase separation. Lesson 27 was conducted as a series of tests (similar to Lesson 30). Some tests were conducted with only tracer particles present in the water, and the later tests were conducted with both tracer particles and sediment particles present. Two different image sets were processed extensively to show the trends that occur in the number of detected particles (p3d) by altering the values of the processing parameters.

The first image set used was test 8 (image 3100-3149). For this test, both tracer particles and sediment particles were present. The image set contains approximately one wave cycle with the wave breaking near the beginning of the image set. Figure 3.18
shows the images 3100, 3110, 3120, 3130, 3140, and 3149 of the image set taken from the right camera Frame A. A significant amount of the sediment suspension occurs between images 3110 and 3120. With the bubbles impinging on the floor of the flume around image 3106, and a cloud of sediment starting to suspend at around image 3112. The advantage of processing this image set is that it contains all of the typical features observed in most wave events: including entrained bubbles, a vortex structure, a large sediment cloud, and onshore and offshore sediment movement. Different image processing settings are applied in a variety of flow situations to examine their effects on phase separation. The default values of the various processing parameters for the non-filtered and filtered settings are summarized in Table 1.

The second image set examined was Test 3 (images 700-749). This image set had no sediment particles present, so all detected particles are tracer particles. This test shows the reliability of the filter by showing how most of the particles present (tracer particles) that are detected using the non-filter settings will be removed after applying the filter settings. The two image sets were used simultaneously to determine the filtering parameters to remove tracer particles. The image sets were processed repeatedly by adjusting the parameters to find the settings that resulted in the most accurate representation of the suspended sediment. The results are explained in more detail in the following section. Table 4.1 lists the most effective parameter settings that were found to filter out the tracer particles.
Table 3.1 Processing settings for the non-filtered and filtered settings

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<tr>
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<td>1</td>
</tr>
</tbody>
</table>
Figure 3.18 Raw images for test 8, image set 3100-3149. Including image 3100 (top left), 3110 (top right), 3120, 3130, 3140, and 3149 all taken with the right camera frame A.
3.4.3 Maximum Radius

As previously discussed, the maximum radius determines the size of the area of pixels that is used to detect local intensity peaks designated as particles. The maximum radius is used in the first step of the detection process; most of the processing steps are dependent on the accuracy of the maximum radius parameter. It is important to note that the maximum radius is not used as a filtering parameter; however, it is important for the filtering process because it designates the support radius, the area that is initially applied to detect potential particles. If the maximum radius is too large, then more than one particle may be included in the detection area, and in effect, a few small particles could be grouped together and processed as one large particle. If the maximum radius is too small, then the detection area will only include a small fraction of the particle’s area; the particle’s size will then be based off of too few pixels leading to errors in the subsequent processing steps.

Figure 3.19 shows the trend of the number of P3D particles detected when the maximum radius is varied and the other parameters are set at the non-filter settings (minimum radius of 1 pixel and an intensity threshold of 10). The trend shows a decrease in the number of particles detected as the maximum radius is increased. As the maximum radius is increased, the amount of decrease between each interval becomes less, so the difference in the number of particles detected by a maximum radius of 2 and 3 is much higher than the difference observed with a maximum radius of 4 and 5. This trend shows evidence that the largest particles on average have a max radius of 3 pixels; when the max radius is increased beyond a value of 3 fewer large particles would be identified as multiple particles and thus a smaller change in particle counts.
Figure 3.19 The average number of P3D particles detected varied based on the max radius for images 3100-3149 in test 8. Images processed with non-filter settings.

Figure 3.20 shows the trends that results from the same test processed with filter settings (minimum radius of 2 and an intensity threshold of 30). The trend observed from these results shows first an increase then a decease as the maximum radius is increased. There is an increase (approximately 500 particles) in the number of particles between maximum radiiuses of 2 to 3; an almost negligible increase (48 particles) is also observed between maximum radiiuses of 4 to 5. The most likely reason why the same trend is not observed between Figure 3.19 and Figure 3.20 is that by applying a filter (minimum radius of 2 and an intensity threshold of 30) most of the small particles are removed, so they will not be grouped together as the maximum radius is increased. The trend also shows that when the tracer particles are removed, the number of large particles detected reaches a maximum at a max radius 3 and decreases thereafter suggesting the max radius should not be increased beyond a value of 3.
Figure 3.20 The average number of P3D particles detected varied based on the max radius for images 3100-3149 in test 8. Images processed with filter settings

A similar test, summarized in Figure 3.21, was performed using the average number of p3d particles for the same image set of 50 frames (images 3100-3149). The figure was the result of processing with a max radius varying from 2-5 pixels at 1-pixel increments and a min radius varying from 1-2 pixels at 0.25 pixels increments. The figure shows a very small difference between trends with a max radius of 2 and of 3, and between a max radius of 4 and 5. The difference between each trend line significantly decreased as the minimum radius increased. In general, the decrease in the number of particles as the minimum radius is increased is not as substantial in the sets processed with a max radius of 4 and 5. The same observation can be made from the trends observed in Figure 3.20 supporting the conclusion that the maximum radius should not be raised above 3 pixels.
Figure 3.21 Number of detected P3D particles when the maximum radius and minimum radius are varied while all other settings are set as non-filtering parameters

In a separate test using the same images (3100-3149), the images were processed with varying maximum radii. The test sequence included a short wave event with the largest number of suspended particles towards the middle of the sequence. Figure 3.22 shows the trend lines observed from these changes. The figure shows that the number of 3D particles (p3d) varied most when the largest amount of sediment was suspended, and that when few particles were present there was little difference in the number of particles detected compared between the different trend lines. The same trends observed in Figure 3.19 are seen in Figure 3.22; the trend was that a maximum radius of 3 pixels will detect the largest amount of particles, and that there is a decrease in the number of particles detected as the maximum radius is increased past 3 pixels. A significant observation for Figure 3.22 is that when few particles are present then there is less of a difference in the number of particles detected for each maximum radius. When the number of particles is higher, the number of p3d particles varies significantly when processed with different
maximum radii. Based on these observations, a maximum radius of 3 was chosen as the filtering parameter used to process the images for the sediment particles.

Figure 3.23 was produced using the same procedure as Figure 3.22 except using images 700-749 from test 3 in Lesson 27. The results from this trend indicate that the maximum radius has little observable effect on the number of detected P3D particles when the images have no sediment particles present and the filter settings are applied.

Figure 3.22 The number of particles detected by varying the maximum radius and with filtering parameters used for the other settings for images 3100-3149 from test 8 Lesson 27
Figure 3.23 The number of particles detected with a variance in the maximum radius with filtering parameters for images 700-749 from test 3 Lesson 27

By taking into account the results from both image sets from test 3 (image 700-749) and test 8 (image 3100-3149). The results show that the number of detected P3D particles decreases when the maximum radius is increased and all other parameters are set as the non-filtering parameters. When the max radius is adjusted while other parameters are set as filtering, then the results show that there is very little difference in the results between a max radius of 4 and 5. There is also an observable increase when the max radius is increased from 2 to 3 and then the results decrease again after the maximum radius is increased past 3. For images that contain no sediment there is little to no effect observed by varying the maximum radius. From these results and other visual checks, the maximum radius was chosen as 3 for the filtering parameter.
3.4.4 Minimum Radius

Unlike the maximum radius, the minimum radius is used as a filtering parameter. The minimum radius helps determine the number of particles; however, the parameter has little effect on the processed size of the detected particle. The minimum radius is a filtering parameter, and it shows that the number of detected P3D particles decreases as the minimum radius is increased. Setting the minimum radius is dependent on the sizes of the particles that are to be detected and the size that needs to be filtered out. The minimum radius is also dependent on the particle detection threshold and the max radius. Both of those parameters affect how the particle size is determined. The best approach to verify the setting for the minimum radius is to compare the particles detected on the raw image with the particles that can be detected visually.

Figure 3.24 shows a raw image with the detected particles processed with filter settings circled in orange. By comparing the left and right figures, it can be seen that the detected particle cloud on the right is roughly the same size and shape of the sediment cloud visually detected on the left. This shows that the minimum radius chosen for the processing was roughly accurate. Figure 3.25 shows a zoomed-in image of the detected particles that can be compared with the particles observed visually. This visual check shows that most of the pixels that seem to belong to sediment particles were detected, and most of the smaller particles that are likely tracer particles were not detected.
Figure 3.24 Raw images of frame 3115; left image shows raw image without matched particles, right image shows raw image with orange circles around the matched particles.

Figure 3.25 Raw image of frame 3115 taken from the right camera Frame A. The matched particles are circled in orange.
In Figure 3.22 images 3100-3149 were processed with a range of minimum particle radii and all other parameters were set at the filter settings. The results show a strong trend where the number of detected particles decreases when the minimum radii is increased. Unlike the results shown in Figure 3.22, Figure 3.26 shows that the difference between the numbers of particles detected between the trend lines with different minimum radii changes very little regardless of how many particles are present. The significance of this observation is that the filter will remove a similar number of particles regardless of how many sediment particles are present; this shows some evidence that the filtering parameter will work throughout the wave cycle. The area where this is not true is between frames 8 to 12 which occurred after the wave breaks as bubbles are present within the viewing window. The bubbles likely hinder the detection of most particles using any of the available settings.
Figure 3.26 The number of particles detected with a variance in the minimum radius with filtering parameters processed on images 3100-3149 of Test 8 Lesson 27

Figure 3.27 was also produced by varying the minimum radius, but this figure was produced by using images 700-749 of Test 3 in Lesson 27. There are no sediment particles present in the image set; by applying a filter, most of the particles should be removed. Figure 3.27 shows that as the minimum radius is increased, the number of detected particles decreased. There is a significant decrease between a min radius of 1 and 1.25. The smallest amount of particles detected occurred when the min radius was 2. This is important because the filter setting should be applicable, regardless of which part of the wave cycle is occurring during the image. Hence, a value of 2 was chosen as the filtering parameter for minimum radius.
The number of particles detected with a variation in the minimum radius processed on images 700-749 of Test 3 Lesson 27 with filter settings.

### 3.4.5 Intensity Threshold

Similar to the minimum radius, the intensity threshold is also a filtering parameter. The intensity threshold is firstly used as a means of filtering in that it does not allow any particles to have an intensity at the center of the particle to be less than the set threshold. The intensity threshold is later used during the same step that the minimum radius is applied to determine the approximate size of the particles. The size of the particle is determined by the Gaussian fit of the intensity and number of pixels within the detection area.

In summary, the intensity threshold is used to determine the size of the particles, and it is used as a filtering parameter to determine which particles are detected. The trend observed by altering the intensity threshold shows that the number of particles detected decreases when the intensity threshold is increased. Figure 3.28 shows this.
trend for images 3100-3149 in Lesson 27. Similar to the min radius, this setting can be verified by comparing the detected particles to the particles seen on the raw image.

Figure 3.29 shows the results of the same processing parameters used to Figure 3.28 but on images 700-749. For the filtering parameters, an intensity threshold of 30 was chosen; this allowed for most of the tracer particles to be removed analysis without eliminating too many sediment particles.

Figure 3.28 The number of particles detected with a variance in the intensity threshold and other parameters set at filter settings processed on images 3100-3149 of Test 8 Lesson 27
Figure 3.29 The number of particles detected with a variance in the intensity threshold and other parameters set at filter settings processed on images 700-749 of Test 3 Lesson 27

3.4.6 Percent Overlap

The percent overlap is used as a filtering step after the centroid of a particle has first been considered. Several “peaks” of light intensity can be contained within the support radius set by the maximum radius. The percent overlap allows more than one peak within the detection area to be considered as a particle as long as the distance between the intensity peaks is greater than the distance set by the percent overlap. As the percent overlap increases, more particles that would have been discarded or grouped together with other peaks as one particle will now be able to be processed individually as a separate particle. Figure 3.30 shows evidence of this with a trend that the number of
p3d particles increases as the percent overlap increases. A percent overlap of 70% was chosen for the filtering settings. This allowed larger particles to be closer together and still be detected. In the experiments most of the sediment is suspended in a cloud so the sediment particles tend to be very close to each other. Allowing the percent overlap to be 70 allows more sediment particles to be detected; since few of the tracer particles would be as close, the increase in percent overlap should not significantly affect the amount of tracer particles detected when the filter settings are applied.

![Graph showing the number of p3D particles detected with different variance in intensity threshold and filter settings on images 3100-3149 of Test 8 Lesson 27.](image)

**Figure 3.30** The number of particles detected with a variance in the intensity threshold and other parameters set at filter settings processed on images 3100-3149 of Test 8 Lesson 27.
3.4.7 Coarse and Fine Search Tolerances

The coarse and fine search tolerances are parameters that are used for the detection of p3d particles; these are particles detected using information from the left, right, and top camera. The search tolerances determine how closely the detected particles in each frame (p2d) have to align between the three camera images to be detected as p3d particles. The number of detected p3d particles increases as the search tolerances are relaxed; however, the accuracy of determining the position of the particles decreases as the tolerances are relaxed. For the filtering settings, a fine search tolerance of 1 pixel and a coarse search tolerance of 2 pixels were chosen. This was based on visual observations, and that the locations of the P3D particles since the sediment particle velocities are not determine, more leniency in pairing is acceptable for these purposes.

Because of the larger percent overlap and search tolerances used for the sediment particles, some of the measured locations of the detected 3D particles were closer than physically possible for the actual size of the sediment particles. A script written in Matlab was used to remove duplicated particles after the 3D particle identification step. A detected particle is considered to be a duplicated particle when the centroid-to-centroid distance between two particles is less than 0.25 mm.

In summary the images were processed based on a range of parameters including maximum radius, minimum radius, intensity threshold, percent overlap, and coarse and fine search tolerances. Each of the afore-mentioned parameters affected the results differently. The maximum radius, minimum radius, intensity threshold, and percent overlap were the parameters used for the 2D particle image processing (p2d); the coarse and fine search tolerances were used for the triplet processing (p3d). The maximum
radius is not used as a filtering parameter, but this parameter is important because the size and position of the detected particle is dependent of the maximum radius. The minimum radius and intensity threshold are filtering parameters, but they also help determine the size of the detected particles. The percent overlap is the parameter that determines how close two “peaks” of light intensities can be and still be considered as two separate particles. The fine and coarse search tolerances are the only parameters that are only applied for the detection of triplet particle processing. These tolerances determine how closely the particles have to match between the three camera frames (left, right, and top) to be considered as valid p3d particles.

The number of particles is plotted using the processed results from images 3100-3149 with two different settings, filter settings and non-filter settings, in Figure 3.31. The plot shows significantly fewer particles when the filter settings are applied. The plot also shows that very few particles are present except during the suspension event. The results from the processing show that an average of 11883 P3D particles were detected using the non-filter settings and an average of 2407 particles were detected using the filtering settings showing that the filtering settings removed 80% of the P3D particles in this test.

Figure 3.32 shows that results from processing images 700-749 with the filtered and non-filtered processing parameters. The results show a significant decrease in the number of detected particles observed between the two settings. With the filter settings, the number of detected particles is below 300, or less than one tracer particle in 1.5 x 1.5 x 1.5 cm$^3$. Hence, the filter settings essentially remove all the fluid tracers in the images. The average number of particles detected for the non-filtered setting was 11314 and the average number for the filtered was 133 with 98.8% removed by the filter.
By observing the results of applying a filter to images with no sediment, Figure 3.32, the results show that over 98% of tracer particles and background noise are removed by the filter. By comparing the results on images with sediment, Figure 3.31, it can be observed that the number of detected particles shows a similar increase for both filter settings when the sediment cloud is present. This shows that similar amounts of sediment is detected by both settings. The conclusion of this is that these filter settings indicate that most of the tracer particles are removed with little reduction in the amount of sediment detected.

Figure 3.31 Number of P3D particles detected using filter and non-filter settings on images 3100-3149 from Test 8 Lesson 27.
Figure 3.32 Number of P3D particles detected using filter and non-filter settings on images 700-749 from Test 3 Lesson 27
4. Experimental Results

The approximate dimensions of the field of view of the V3V camera are 120 (X) by 120 (Z) by 100 (Y); after processing and plotting the volume is slightly decreased so that the results plotted on tecplot have a volume of 120 (X) by 104 (Z) by 56 (Y). Figure 4.1 shows the wave as it breaks over the measurement area. A separate set of experiments were performed in clear water to measure the wave transformation along the flume at varying intervals with either 2 or 4 trials for each position. Table 4.1 summarizes the results from the wave measurements. The start of each wave for these measurements was synchronized to ensure consistency. The duration of each wave record is 81.92 s, and the sampling interval is 0.02 s. Figure 4.2 shows the measured wave elevation time histories at selected locations. The top plot (d=0.3716 m), where d is the still water depth, is from the wave gage location closest to the wave generator. The bottom plot (d=0.1060 m) is from the wave gage location closest to the still water shoreline. The V3V measurement volume, used in the main experiment, is located around d=0.202 m. The mean wave height and the wave setup/setdown were computed from the last 10 complete wave periods. The breaking point (d=0.2889 m) is defined as the location where the maximum wave height is measured.
Figure 4.1 Side view of a wave breaking over the approximate measurement volume (outlined by the black rectangle).
Table 4.1 Summary of the results from the wave measurements. The table includes the distance from the still water shoreline \((x)\), the still water depth \((d)\), mean water level \((\eta_{\text{mean}})\), wave height \((H)\), and the number of trials observed at that location.

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Figure 4.2 Measured wave time elevations at six separate locations with the still water depth represented by \( d \). The top plot is the location near the wave generator and the bottom plot is the location that was measured nearest to the shoreline.
The surf similarity parameters, $s/\sqrt{H_0/L_0}$, is 0.33; where $s$ is the beach slope of 2.5% and $H_0/L_0$ is the wave-height-to-wave-length ratio in deep water. Therefore, the breaking waves are technically classified as spilling waves. Visual inspection shows that waves were transitioning between spilling and plunging waves as all waves produced distinct plunger vortices. Figure 4.3 shows the variation of the wave-height-to-water-depth ratio, $H/h$, and mean water level, $\eta_{mean}$, with the horizontal distance from the still water shoreline, $x$. The mean water depth is $h = d + \eta_{mean}$. The plots in Figure 4.3 are constructed using the measured data in Table 4.1. The maximum $H/h$ ratio is 0.78 at breaking and decreases to around 0.5 near shore. This is consistent with the wave transformation of spilling breakers. The maximum wave setdown and setup measured are -13.6 mm and 4.2 mm, respectively. As seen in Figure 4.2, the V3V measurement volume (around $x=6.9$ m) is located in the transition to the inner surf zone where the $H/h$ ratio is changing slowly.

The wave data in Table 4.1 and Figure 4.3 correspond to a quasi-steady state in the wave flume. A long period of time is required to establish a steady-state wave condition, therefore the velocity measurements were conducted under transient wave conditions. Velocity measurements were started at $t=5$ s after the wave generation to reduce the number of still images captured before the first wave approached the V3V measurement volume (see the wave recorded at $d=0.202$ m). The last velocity field was taken at $t=31.67$ s. This gives a total of 7 complete wave cycles recorded for the velocity field measurements. The first two waves do not break until they are onshore past the test section. Plots of measured $H/h$ ratios versus cross-shore distance $x$ can be constructed for
the five breaking waves using the synchronized wave records such as those shown in Figure 4.3. For these five breaking waves, the breaking point varies from wave to wave. The maximum H/h ratios are 0.81, 0.78, 0.77, 0.79, and 0.80 at d=0.2724, 0.2889, 0.2889, 0.2889, and 0.2889 m, respectively. Except for the first wave, the location of the breaking point and maximum H/h ratio are close to the average values obtained from 10 waves in the latter part of the wave record.

![Graph](image)

Figure 4.3 The variation of the wave-height-to-water-depth ratio, H/h, and mean water level, \( \eta_{\text{mean}} \), with the horizontal distance from the still water shoreline along the X-axis on both plots.
4.1 Case 1, Test 14, Image 6770-6815: Splash creating a ring of sediment followed by a counter-clockwise columnar vortex.

Images 6770 to 6815 shows a wave event that produced a sediment splash and a vertical columnar vortex. The wave-induced velocity changed from offshore to onshore in frame 6762 and reached the maximum positive velocity in frame 6766. A downburst of turbulent fluid impinged on the bottom near the offshore side of the measurement volume in frame 6771. The splash resulting from the breaking wave created a ring of suspended sediment that moved radially outward from the impact zone. Figure 4.4 shows a sequence of raw images from the top camera depicting the expanding ring of ejected sediment. The suspended sediment travels more slowly in the vertical direction than in the horizontal directions, suggesting much higher horizontal velocities compared to vertical velocities.

Figure 4.5 shows the distribution of suspended induced by the downburst impinging on the bottom. The impact of the downburst created a strong upward flow (red contour) around the impingement zone. Inside this zone, the fluid velocity is downward (blue contour). Most of the suspended sediment is located in the upward flow region. The velocity vectors in the horizontal plane are shown with the contours of the vertical velocity at a height approximately 4 mm above the bottom at Y=-68 mm, and the brown spheres represent all the captured sediment particles in the measurement volume.

The magnitude of the vertical velocity and horizontal velocity can be determined using the reference vector and the scale of the vertical velocity contours. The vertical velocity is considerably smaller than the horizontal velocity in this splash event; however, the vertical velocity had to be present for the sediment to be suspended. This
can be seen by comparing the locations of the suspended sediment in Figure 4.5 to the area that experiences a vertical velocity of approximately 0.04 m/s or greater. The sediment’s fall velocity is about 0.033 m/s.

A swirling cloud of sediment appeared behind the sediment ring in frame 6778. The cloud continued to grow as sediment particles were trapped and suspended to higher elevations to form a vertical column. The wave-induced velocity changed from onshore to offshore in frame 6784. After flow reversal, the suspended sediment was transported through the measurement volume from onshore to offshore. Figure 4.6 shows a sequence of images from the left camera, which clearly depict the growth of the sediment cloud and its offshore transport by the wave-induced velocity.

Figure 4.7 shows 3D plots of the distribution of suspended sediment in the columnar vortex. The measured velocity field is shown at a height of 4 mm above the bottom. The iso-surface of vertical vorticity ($\omega_Y$) shows that the counter-clockwise vortex seen in Figure 4.7 is a vertical vortex structure traveling with the downburst, and it is in this vortex tube that the highest concentration of suspended sediment is found. In frame 6784, the wave-induced velocity has changed direction. The vortex tube and the trapped sediment are moving offshore and out of the measurement volume. Figure 4.8 shows the cloud of suspended sediment trapped within the columnar vortex for images 6778, 6780, 6782, and 6784; these images correspond to the same frames as the three-dimensional plots shown in Figure 4.7. The velocity vectors in the horizontal plane are shown with the contours of vertical velocity at a height of 4 mm above the bottom and all the detected sediment particles.
Figure 4.4 Image sequence showing sediment suspensions produced by the impact of a downburst on the bottom. From top to bottom: frames 6772, 6774; 6776, 6778; 6780, 6782. The images are from the top cameras.
Figure 4.5 Distribution of suspended sediment induced by a downburst impinging on the bottom from test 14. The longitudinal velocity $U$ and transverse velocity $W$ are shown at a $Y=68$ at a height approximately 4 mm above the bottom. The bottom is located at $Y = -72$ mm. The contour variable is vertical velocity $V$ in m/s. All the detected sediment particles are shown.
Figure 4.6 Image sequence showing sediment suspensions produced by the impact of a downburst on the bottom. From top to bottom: frames 6778, 6780; 6782, 6784; 6786, 6788. The images are from the left camera.
Figure 4.7 Three-dimensional plot of suspended sediment distribution. Iso-surface of vorticity in the vertical ($Y$) direction are shown in green color for $\omega_Y = 30 \text{ s}^{-1}$. Sediment particles are shown up to a height of 30 mm above the bottom to exclude a large mass of air bubbles entrained by the plunging breaker.
Figure 4.8 The sediment cloud caught within the vortex in test 14. The longitudinal velocity $U$ and transverse velocity $W$ are shown at a height of 4 mm above the bottom. The contour variable is vertical velocity $V$ in m/s.
4.2 Case 2, Test 17, Image 8100-8153: Large counter-clockwise transverse vortex creating a strong sediment suspension

In this case, a large counter-clockwise transverse vortex created by wave impingement suspended a significant amount of sediment. The wave-induced velocity changed from offshore to onshore in frame 8099 and reached the maximum positive in frame 8102. A large counter-clockwise vortex descended into the measurement volume and reached the bottom near the onshore side when the back face of the wave passed over. The vortex was highly effective in suspending sediment.

Figure 4.9 shows the formation and evolution of a large sediment cloud induced by the vortex in a sequence of raw images captured by the left camera.

Figure 4.10 shows a 3D perspective plot of the measured velocity field in the longitudinal-vertical (X-Y) plane at four different transverse (Z) positions. The counter-clockwise vortex is a vortex loop with a base that spans the width of the measurement volume; this can be seen in frame 8110. The vortex tube impinged on the bottom and entrained sediment along its entire length, with the highest initial sediment concentration located between \( Y = -680 \) and -700 mm on the near side to the camera (frame 8113).

Figure 4.11 shows representative results for a slice of the flow field in this region. The distribution of suspended sediment is plotted with the measured fluid velocity field at six different instances of time between frames 8113 and 8124. In Figure 4.11, the measured velocity field in the X-Y plane is shown at \( Z = -700 \) mm, and the distribution of suspended sediment is shown in a 20-mm thick slice between \( Z = -690 \) and -710 mm.
Figure 4.9 Image sequence showing sediment suspensions behind a transverse vortex impinging on the bottom. From top to bottom: frames 8113 (left), 8114 (right); 8115, 8116; 8120, 8124. The images are from the left camera.
Figure 4.10 Three-dimensional perspective plot depicting vortex tube descending to the bottom (left plot) and initial distribution of suspended sediment (right plot). Measured velocity fields in the longitudinal-vertical (X-Y) plane are shown at $Z = -670, -700, -730$ and $-760$ mm. The contour variable is spanwise vorticity $\omega_z$ in $\text{s}^{-1}$.

Figure 4.11 shows that significant sediment suspension begins in frame 8113 and occurred directly underneath the vortex. The suspended sediment was carried away from the bottom in the upward flow behind the vortex. Some sediment particles were trapped by the vortex to circulate around the vortex core, but many other particles were spun out of the vortex into the free stream behind the vortex (frames 8114 to 8116). In frame 8120, the vortex moved out of the measurement volume, and the wave-induced velocity changed direction from onshore to offshore. After flow reversal, the suspended sediment in the free stream was transported offshore by the seaward mean flow.

Figure 4.12 presents the two-phase flow measurements from the moments around the initiation of sediment suspension. The distribution of suspended sediment is presented with contour plots of fluid velocity magnitude (left plots) and vertical velocity (right plots) to examine the physical processes by which bottom sediment was entrained and carried away from the bed. These plots show that the instantaneous velocity magnitude under the vortex reached a maximum value between 0.2 and 0.25 m/s at $X = -$.
40 mm in frames 8110 and 8111. Because the time scale of impact is very short, the wall boundary layer induced by the vortex must be extremely thin. The resulting fluid shear stress would be large enough to mobilize sediment. However, significant sediment suspension is not observed at this location until frame 8113, when the backside of the vortex arrived and the dislodged sediment were entrained into the strong upward flow behind the vortex. The upwash reached a maximum vertical velocity of about 0.15 m/s in frame 8115, which is much greater than the sediment fall velocity of about 0.033 m/s, and allowed the suspended sediment to be carried to great heights (up to about 30 mm above the bottom).

Figure 4.11 and Figure 4.12 show that the time scale of vertical transport of sediment by the vortex-induced flow from initiation of sediment motion to reaching the maximum height is only about 0.2 s. This is due to convective transport by the upwash induced by the vortex, which allows suspended sediment to be carried more quickly and to greater heights than could normally be result from boundary-layer turbulence generated by the wave motions alone.
Figure 4.11 Distribution of suspended sediment induced by a vortex impinging on the bottom. The longitudinal velocity $U$ and vertical velocity $V$ are shown at transverse cross section $Z = -700$ mm. The distribution of suspended sediment is shown in a 20-mm thick slice between $Z = -690$ and -710 mm. The contour variable is spanwise vorticity $\omega_z$ in s$^{-1}$. 
Figure 4.12 Same as Figure 4.11, but the contour variables are velocity magnitude (left plots) and vertical velocity (right plots) in m/s.
Figure 4.12 (Cont.)
4.3 Case 3, Test 18, Image 8810-8870: Sediment suspension behind two consecutive vortices

The wave-induced velocity changed from offshore to onshore in frame 8815 and reached a maximum positive velocity in frame 8819. The wave impingement comes into view in image 8819. Figure 4.13 and Figure 4.14 show the raw images taken from the right camera for frames 8820 to 8838. These two figures show the wave impingement and the formation of the sediment clouds. In image 8820, a small sediment cloud is formed when a large vortex passed through the measurement volume close to the bottom. A few frames later in frame 8826 the same sediment cloud is still present, but now another sediment cloud has been formed behind a second vortex that impinged on the bottom inside the measurement volume. In frame 8828, the sediment cloud behind the second impingement is larger and denser than the sediment cloud formed by the first vortex.

Figure 4.15 shows the plotted velocity vectors and contours of the z-vorticity, the figure shows that there was a smaller vortex directly in front of the large impingement shown in the raw images in Figure 4.13 and Figure 4.14. Figure 4.15 shows the progression of the first vortex. The vortex moves across the top of the field of view, suspends very little sediment, and did not impinge on the bottom inside the measurement volume. The distribution of suspended sediment is presented as red spheres with contour plots of the span-wise vorticity $\omega_z$ in s$^{-1}$ at $Z= -685$ mm and vector field of the fluid velocity magnitude. In the bottom plot of Figure 4.15, there appears to be a small cloud of sediment in the region with negative vorticity (blue contour region); however, by comparing this region with the corresponding raw image it can be concluded that the
detected particles in that region are actually air bubbles from the breaking wave. A similar comparison shows that the region with higher positive vorticity, $\omega_Z = 20 \text{ s}^{-1}$ (red contour) coincides with the only region that sediment suspension can be seen in the raw images.

Figure 4.16 shows the progression of the second vortex for Frames 8826 to 8831. The distribution of suspended sediment is represented as red spheres with contours of the span-wise vorticity $\omega_Z$ in $\text{s}^{-1}$ at $Z= -685$ mm and the velocity vector field. The blue area that contains some of the detected particles represents the disorganized impingement from the broken wave. Similar to Figure 4.15, some of the detected particles, especially what is found where the vorticity contours are negative, likely correspond to air bubbles and not suspended sediment. It is important to compare the detected sediment in the plotted figures with the sediment that can be observed in the raw images. The second vortex is directly offshore behind the impingement in Frame 8826. This vortex is seen just as it is moving into the bottom of the field of view. The second vortex is much smaller than the first vortex in this wave event; however, compared with the first vortex, the second vortex suspended a much larger cloud of sediment. The sediment cloud resulting from the second vortex also suspended the sediment much higher than the first. The second vortex became disorganized quickly. The sediment cloud created from that vortex dispersed and moved offshore out of the field of view.
Figure 4.13 Image sequence showing the progression of the vortex impingement. From top to bottom: frames 8820 (left), 8822 (right); 8824, 8826; 8828, 8830. The images are from the right camera. The approximate location of the first and second vortex are annotated in image 8822 and 8826, respectively.
Figure 4.14 Image sequence showing the progression of the vortex impingement. From top to bottom: frames 8832 (left), 8834 (right); 8836, 8838; 8840, 8842. The images are from the right camera.
Figure 4.15 The first vortex after the breaking wave moving through the top of the field of view. The distribution of suspended sediment is shown in a 20-mm thick slice between $Z = -695$ and $-675$ mm. The contour variable is span-wise vorticity $\omega_Z$ in s$^{-1}$ at $Z = -685$ mm. The sediment is represented by the red spheres.
Figure 4.16 Second vortex after breaking wave shown as it hits the bottom inside the field of view and suspends a dense cloud of sediment. The distribution of suspended sediment is shown in a 20-mm thick slice between $Z = -695$ and $-675$ mm. The contour variable is span-wise vorticity $\omega_Z$ in $s^{-1}$ at $Z = -685$ mm. The area that contains mostly air bubbles is outlined in black.
The case is notable because the wave impinged in the center of the field of view, and two consecutive vortices are observed. This second cloud was difficult to detect because of the air bubbles, so the plotted figures are compared with the raw images to locate the regions that contain suspended sediment and exclude the air bubbles. The event was typical in that large portions of the view were obstructed by bubbles and this added difficulty in determining the validity of the detected sediment particles. In this case, and in many other cases, it is important to compare the raw images with the Tecplot figures to note the detected sediment positioning and the general flow characteristics to help verify the plotted results. A second notable observation of this case was the second vortex. In several cases, the second vortex appears as a vertical or columnar vortex depending on which part of the vortex loop was within the field of view. The sediment cloud that resulted from this vortex was dense and kept its shape until it moved out of the field of view. This is typical in the cases that contain a second vortex.
4.4 Case 4, Test 26, Image 12650-12700: Sediment suspension around the front of the impingement zone

This case shows a clear view of initial sediment suspension resulting from a splash from a breaking wave. The splash was followed by sediment suspension within a detached shear layer rolled up into a clockwise vortex. The wave-induced velocity changed from offshore to onshore in frame 12653. The wave broke just offshore of the field of view and the downburst impinged on the bottom near the far offshore corner of the measurement volume. The impact created a large splash around the impingement zone that expanded rapidly outward and ejected sediment from the bed in the form of a ring the expanded radially outward as the event progressed. The event occurred around a flow reversal. It can be tracked from frame 12662 to frame 12664 before entrained air bubbles reach the bottom and obscured the field of view. These measurements provide a rare glimpse of the early stage of sediment suspension in front of a downburst, where good data are difficult to obtain due to visual obstruction resulting from entrained air bubbles. Figure 4.17 shows the captured raw images from the right and top cameras. For reference, the longitudinal velocity reached the maximum positive in frame 12656.

Figure 4.18 shows three-dimensional plots showing the vortex ring and the surrounding sediment suspension. The measured velocity field is shown at Y = -65 mm. The bottom location is Y = -72 mm. The iso-surface of the vorticity magnitude ($\omega_{mag}$) shows that the vortex structure traveled radially outward with the highest concentration of sediment suspended in front of the structure. The initiation of sediment motion occurred at the location where the deflected flow created by the downburst induced high flow velocity (0.2 to 0.3 m/s) adjacent to the bed (see Figure 4.19). The suspended sediment
was carried away as the deflected flow separated from the bottom and reached a maximum height of about 30 mm. The shear layer formed by the deflected flow then rolled up trapping the suspended sediment inside the ensuing vortex. The sediment quickly dispersed and settled or was carried outside the field of view. It may be inferred that the clockwise vortex must have dissipated quickly as no remnant of the structure was seen passing through the measurement volume after the flow reversal.

Figure 4.19 shows the measured velocity field and distribution of suspended sediment in both 3D view (left plots) and side view in the XY plane (right plots). The 3D plots show that the downburst is very large and only a small portion of it around the front and side was captured in the measurement volume. The vertical velocity in the deflected flow reached a magnitude of 0.1 to 0.15 m/s (yellow and orange contours) at just a few millimeters above the bottom, far exceeding the sediment fall velocity of about 0.03 m/s. The side view shows the measured velocity field \( (U, V) \) in the longitudinal-vertical plane at \( Z = -764 \) mm near the front of downburst. The distribution of suspended sediment is shown in a 20-mm thick slice about this plane. The contour variable is the magnitude of the measured velocity \( (U, V, W) \) in m/s. These plots shows that the flow adjacent to the bed reaches a velocity magnitude of between 0.2 and 0.3 m/s when it separates from the bed. Sediment particles are carried upward by the deflected flow and trapped in a clockwise vortex formed by the roll-up of the shear layer.
Figure 4.17 Image sequence showing sediment suspensions in front of a downburst. From top to bottom: frames 12662, 12663, and 12664. The left images are from the right camera, and the right images from the top camera.
Figure 4.18 Three-dimensional plot of suspended sediment distribution. Iso-surface of vorticity magnitude is shown in green color for $\omega_{mag} = 25$ s$^{-1}$. Sediment particles are represented by the red spheres. The velocity magnitude is shown in the Y plane at Y=$-65$ mm.
Figure 4.19 (Left plots) 3D perspective of sediment suspensions in front of a downburst. The measured velocity field in the horizontal ($X$-$Z$) plane is at $Y = -65$ mm. The contour variable is vertical velocity in m/s. (Right plots) Measured velocity field in the longitudinal-vertical ($X$-$Y$) plane at $Z = -764$ mm. The contour variable is the velocity magnitude. The distribution of sediment is shown for $-774 < Z < -754$ mm.
4.5 Case 5, Test 30, Image 14750-14789: An impingement of a large span-wise counter-clockwise vortex resulting in the suspension of a dense cloud of sediment.

In this case a large vortex impinged on the bottom in the field of view and as a result a dense cloud of sediment was suspended just offshore of the vortex with a strong correlation between the suspension of the sediment and the strong upward vertical velocity. The wave-induced velocity changed from offshore to onshore in frame 14762 and reached a maximum positive in frame 14765. The wave broke just offshore of the field of view. The turbulent fluid moved down into the field of view, and a large counter-clockwise vortex formed spanwise across the measurement volume. The vortex moved downward and reached the bottom of the field of view in frame 14770; a large cloud of sediment was then suspended directly behind the vortex. The sediment cloud moved onshore behind the vortex until approximately frame 14783 when both the vortex structure and the sediment cloud moved outside the measurement volume. The flow direction reversed around frame 14787. The vortex had largely dissipated by this point and was too disorganized to discern. The sediment was dispersed and did not return through the field of view as a sediment cloud.

Figure 4.20 shows the raw images for 14764-14770 taken from the left camera. Figure 4.20 shows the progression of a counter-clockwise vortex as it moved down into the measurement volume until it reached the bottom of flume in frame 14770. It is noted that the vortex seen in Figure 4.20 contains a lot of bubbles that distort the plotted results. Figure 4.21 shows the raw images from 14772 to 14782 also taken from the left camera. This series of images show the suspension and movement of the sediment cloud behind the vortex. Figure 4.21 shows that the size of the sediment cloud remains approximately
constant from frame 14772 to frame 14776; in frame 14778 the sediment cloud begins to disperse and move more quickly onshore out of the field of view.

Figure 4.22 shows the representative results for a slice of the flow field. The distribution of suspended sediment is plotted with the measured velocity field in the X-Y plane shown at \( Z = -728 \) mm for every other image from images 14766 to 14776. The distribution of the suspended sediment is shown in a 20 mm thick slice between \( Z = -718 \) and \(-738 \) mm. The detected particles were blanked just in front of the area that experience high air entrainment so that the detected suspended sediment particles would correspond more closely with the sediment observed in the raw images. The contour variable is spanwise vorticity \( \omega_Z \) in s\(^{-1}\). The vortex resulting from this wave event is rotating approximately perpendicular to the X-Y plane. Figure 4.22 shows that significant sediment suspension begins in frame 14770 directly behind the vortex. The sediment was suspended upward in the flow behind the vortex and formed a dense cloud. The cloud grew, dispersed, and eventually traveled onshore behind the vortex.

Figure 4.23 shows the representative results for the same slice as Figure 4.22 of the flow field; however, this figure highlights the effects of vertical velocity on the initial sediment suspension. This figure shows the velocity vectors in the X-Y plane plotted with the contours of vertical velocity for \( Z = -728 \) mm. Image 14770 is the first frame in the series that shows a distinct sediment cloud. Figure 4.23 shows that the maximum vertical velocity is greater than 0.3 m/s where the sediment suspension occurs; the fall velocity of the sediment is approximately 0.033 m/s so this figure shows that the sediment starts to suspend as the vertical velocity exceeds the fall velocity.
Figure 4.20 Raw images 14764 to 14782 taken with the left camera showing the progression of the wave event and the following suspension and movement of the sediment cloud. From top to bottom: frame 14764 (left), 14766 (right), 14768, and 14770.
Figure 4.21 Raw images taken from the left camera for images 14772 to 14782. From top to bottom: frame 14772 (left), 14774 (right), 14776, 14778, 14780, and 14782.
Figure 4.22 The distribution of suspended sediment cloud by a vortex impinging on the bottom. The longitudinal velocity $U$ and vertical velocity $V$ are shown at transverse cross section $Z = -728$ mm. The distribution of suspended sediment is shown in a 20-mm thick slice between $Z = -718$ and -738 mm. The contour variable is spanwise vorticity $\omega_Z$ in $s^{-1}$. The reference vector is in the top right corner representing a vector of 0.5 m/s.
Figure 4.23 The distribution of suspended sediment cloud by a vortex impinging on the bottom. The longitudinal velocity $U$ and vertical velocity $V$ are shown at transverse cross section $Z = -728$ mm. The distribution of suspended sediment is shown in a 20-mm thick slice between $Z = -718$ and -738 mm. The contour variable is vertical velocity ($V$) in m/s.
4.6 Case 6, Test 16, Image 7840-7870: Sediment cloud suspended with vertical velocity and stay in suspension

In this image set, a small cloud of sediment was suspended as the wave-induced water velocity moved in the offshore direction. For reference, the wave impinged near the field of view at approximately frame 7840. After the impingement, the flow was reversed and flowed offshore. The counter-clockwise vortex from the impingement moved offshore with the mean flow. The vortex is difficult to see with the total velocity vectors, but can clearly be seen by plotting the turbulent velocity. A small area in images 7850-7857 experienced an upward vertical velocity that resulted in the suspension of a cloud of sediment. After the vertical velocity decreased the sediment cloud, previously suspended by the vertical velocity, continued to move with the strong horizontal water velocity offshore.

Figure 4.24 shows the raw images from 7849 to 7854 taken from the left camera. The image sequence shows a small sediment cloud getting suspended at 7849 and moved offshore past 7854 when the sediment cloud was moved out of the field of view. Figure 4.25 shows X-Y plane with the turbulent velocity field with the contours of vertical velocity. The vertical velocity contours represent the total vertical velocity including the average and turbulent velocity. The X-Y plane shown is located at Z = -680 mm; the sediment is included between Z= -670 and -690 mm. The figure shows a large counter clockwise vortex. The suspension of the sediment cloud is shown suspending just offshore of the increase in positive vertical velocity and the counter clockwise vortex. The area that experienced the initial suspension was in the region with a positive vertical velocity of approximately 0.04 m/s or higher.
Figure 4.26 shows the plots for image 7850 with the horizontal velocity field at $Y = -68$ mm and the detected sediment particles represented by black spheres. The contour variables of the plots are varied for each plot; the plots show contours of horizontal velocity, vertical velocity, vorticity magnitude, turbulent kinetic energy, total shear stress, and turbulent shear stress. The horizontal velocity is the resultant velocity of the velocity components in the X and Z direction. The relationship between horizontal velocity and sediment suspension is weak; there is a small area that experienced a horizontal velocity of 0.3 m/s or higher where sediment suspension was observed. The correlation between sediment suspension and vertical velocity was much stronger. The plot shows that the highest concentration of suspended sediment is found in regions with vertical fluid velocity of 0.03 m/s or greater; for reference, the sediment fall velocity is about 0.033 m/s.
Figure 4.24 Raw images 7849 to 7854 taken with the left camera following the suspension and movement of the sediment cloud. From top to bottom: frame 7849 (left), 7850 (right), 7851, 7852, 7853, and 7854.
Figure 4.25 The turbulent velocity field plotted with contours of vertical velocity on the X-Y plane at Z=-680 mm. The sediment is included between Z=-670 and -690 mm.
Figure 4.26 The X-Z velocity field for image 7850 at Y=-68 mm; the sediment is shown from the bottom of the measurement volume up to Y=-63 mm. From top to bottom: horizontal velocity (U) in m/s (left), vertical velocity (V) in m/s (right), the magnitude of vorticity (ω-magnitude) in s⁻¹, turbulent kinetic energy (k) in cm²/s², total shear stress (τ-total) in cm²/s², and turbulent shear stress (τ-turbulent) in cm²/s².
The total shear stress and turbulent shear stress show similar contour patterns to the vertical velocity. The turbulent shear stress is considerably smaller than the total shear stress with corresponding values of turbulent shear stress less than half the values of total shear stress. Despite this difference, the sediment suspension occurs in areas that experienced the relative maximum stresses for each plot. The plot showing the contours of turbulent shear stress shows that the sediment suspension seems to occur in areas that experience a shear stress of 20 cm$^2$/s$^2$ or greater. The plot showing the contours of total shear stress show that the sediment suspension occurred in areas that experienced a total shear stress of 50 cm$^2$/s$^2$ or greater. In both of these plots, the correlation between fluid shear stress and sediment concentration is strong. The other plots in the figure show a weak correlation between sediment suspension and vorticity magnitude or kinetic energy.
4.7 Case 7, Test 34, Image 16760-16810: Strong wave impingement resulting in two separate sediment suspension events

In this wave event, the wave broke and impinged into the onshore side of the field of view at frame 16770. The impingement resulted in the suspension of a ring of sediment that quickly spread radially outward. Two sediment clouds were formed from the same splash; the first sediment cloud from the impact of the jet and the second from the impingement of the vortex. This sediment cloud suspended less sediment and moved quickly seaward out of the field of view. The average horizontal water velocity was not strongly seaward or shoreward during the initial suspension event. The fast movement of both of the sediment clouds out of the field of view seems to have resulted from the water velocity created directly from the impingement. The raw images from the left and top camera are shown in Figure 4.27, depicting the impingement of the breaking wave and the resulting suspension event.

A second suspension event formed as the first sediment cloud was just about out of the field of view. This sediment cloud was considerably larger and denser than the one created in the first suspension event. This sediment cloud formed across the flow field in the Z direction. The sediment cloud initially moved very little as the suspension event progressed. The sediment within the cloud was suspended higher and dispersed. All that was left of the sediment cloud after most of it was dispersed moved offshore out of the field of view when the water velocity increased and moved in the offshore direction. Figure 4.28 shows the raw images of the left and top camera for the second suspension event.
The first sediment event is shown with the contours of different flow parameters to examine the correlations between the sediment distribution and individual flow parameters. Figure 4.29 shows frame 16771 plotted with the velocity field in the X-Z plane at $Y=-68$ mm. The detected suspended sediment is represented by black spheres. The sediment is within the interval from the bottom of the measurement volume ($Y=-72$ mm) up to $Y=-63$ mm. Several bubbles were entrained in the impingement. The raw images show that the initial suspension was in the shape of a ring, with very little suspension occurring in the center of the ring. The plots show some sediment particles in the center of the ring. From comparison with the raw images, these particles correspond to entrained air bubbles and not suspended sediment. Each of the plots has a different flow parameter represented with contours. The contour variables are horizontal velocity, vertical velocity, turbulent kinetic energy, total shear stress, and turbulent shear stress.

The plots showing vertical velocity and shear stress (total and turbulent) show a strong correlation between the areas that experience relatively large vertical velocity or shear stress and the areas where the suspended sediment concentrations are high. The contour variables that show weaker correlation with sediment suspension are horizontal velocity, turbulent kinetic energy, and the vorticity magnitude.

The raw images in Figure 4.28 show that the second sediment event started around image 16777. Figure 4.30 and Figure 4.31 show the corresponding plotted frames for the second sediment event from the side and top view. Figure 4.30 shows the vortex structure just prior to its impact on the bottom of the flume. The left plots show the side view with the velocity field and contours at $Z=-750$ mm. The right side of Figure 4.30 shows the top view of the event. Each plot on the right side indicates the location of the
slice showing the velocity field and the contours. The vortex in this wave event was complex and shifted direction throughout the event. The slices are shown at the vertical location that corresponded to the near center of the vortex for that frame; the slices show the development of the vortex as it moved down to the bottom of the flume.

Figure 4.31 shows the sediment event after the vortex impacted the bottom of the flume. Similar to Figure 4.30, this figure shows the top and side view of the event. It also includes the detected sediment represented by the black spheres. The left plots showing side view include the sediment in a 4 cm wide section (Z=−770 to −730 mm); the right plots show only the sediment within 6 mm of the bottom (up to Y=−68 mm). The figure shows that some of the sediment gets suspended directly into the vortex, but as the event progresses more of the sediment is suspended just offshore of the vortex and does not seem to get trapped within it.

The most significant amount of vorticity is around the Z-axis; however, the fluid velocities seen from the top view (X-Z plane) show a counter-clockwise rotation around the Y-axis. The three-dimensional form of the structure can be inferred from the side and top view in Figure 4.30 and Figure 4.31. The 3D vortex structure is initially seen in Frame 16770 at a 45-degree angle to the X direction in the X-Z plane; throughout the event, the structure rotates to approximately parallel to the Z-axis as it impinges into the bottom of the field of view. The structure appears to impact the bottom at this point and suspends sediment across along the entire depth of field (Z-axis).
Figure 4.27 Raw images of sediment suspension event. Left images show the raw images taken from the left camera. Right images show the raw images taken from the top camera. The images are, from top to bottom, 16766, 16768, 16770, 16772, and 16774.
Figure 4.27 (continued).
Figure 4.28 Raw images of the second suspension event from the left camera including images 16775 (top left), 16777 (top right); 16779, 16781; 16783, and 16785.
Figure 4.29 The plots for image 16771 with the measured horizontal velocity field at y=-68 mm and the detected sediment particles represented by black spheres included between Y=-72 mm and Y=-68 mm. From top to bottom, the contour variable in each plot is horizontal velocity (left) m/s, vertical velocity (right) m/s; vorticity magnitude ($\omega$ magnitude) s$^{-1}$, turbulent kinetic energy (k) cm$^2$/s$^2$; total shear stress ($\tau$ total) cm$^2$/s$^2$, and turbulent shear stress ($\tau$ turbulent) cm$^2$/s$^2$. 
Figure 4.30 the vortex structure outlined by the Z-vorticity just prior to its impact on the bottom of the flume. The left plots show the side view with the velocity field and contours at $Z = -750$ mm. The right side shows the top view of the event. Each plot on the right side indicates the location of the slice showing the velocity field and the contours.
Figure 4.31 shows the vortex structure outlined by the Z-vorticity just prior to its impact on the bottom of the flume. The left plots show the side view with the velocity field and contours at Z=-750. The right side shows the top view of the event. Each plot on the right side indicates the location of the slice showing the velocity field and the contours. The left plots showing side view include the sediment in a 4 cm wide section (Z=-770 to -730); the right plots show only the sediment within 6 mm of the bottom (up to Y=-68).
4.8 Case 8, Test 6, Image 2660-2690: A columnar vortex observed after the wave breaking.

In this case, a columnar vortex moved onshore into the field of view after a wave broke. The wave broke just offshore outside the field of view and the bubbles and impingement resulting from the breaking came into view around frame 2660. The frames from 2660 to 2669 are mostly obscured with bubbles, and the velocity and minimal sediment suspension occurring during those frames resulting from the wave is difficult to track. The bubbles moved out of the viewing window at frame 2669; in frame 2670, a small cloud of sediment began to suspend and moved slowly onshore. Between frames 2670 and 2680 the cloud of sediment moved slightly onshore until the average direction of the wave induced water velocity reversed and moved back offshore during the trough part of the wave cycle. Figure 4.32 shows the sequence of these events including the even frames from 2670 to 2680.

The frames were plotted to show the iso-surface of the magnitude of vorticity and the detected sediment particles. The plots of the frames can be seen in Figure 4.33 with the velocity field shown in the X-Z plane at Y=-67 mm, and the iso-surface, represented by the blue color, showing the vorticity at \( \omega_{\text{mag}} = 30 \, \text{s}^{-1} \). The sediment particles are represented by the red spheres. The figure shows that the sediment cloud closely followed the vortex structure. It also showed that the structure moved with the direction of the flow of the water velocity. The structure, and as a result the cloud of sediment, moved very slowly and only a short distance until it became disorganized and moved out of view.
In contrast, the counter-clockwise span-wise vortices seen in the previous cases are directly connected to the breaking waves and occur only shortly after the wave impingement. In these cases, the counter-clockwise vortices move quickly through the viewing window and sometimes can be seen moving back down through the viewing window as the water is drawn back before the next wave breaks. These vortexes move significantly farther than the observed columnar vortex. In this specific case, the columnar vortex occurred several frames after the wave breaking and impingement. The columnar moved very slowly into the viewing window and only moved a slight distance onshore before moving back offshore. The column vortex also is more disorganized and seems to have a shorter life span than the large, span-wise counter-clockwise vortex.

Similar with the counter-clockwise vortex, both seem to follow the general direction speed of the flow of water. The nature of the second vortex in how it looks while within the field of view is likely related to the location where the wave breaks and how it broke.

It seems very likely that the columnar vortex is one of the “arms” of the initial vortex loop that has broken off and was left behind as the main part of the spanwise counter-clockwise vortex moved more quickly forward. This observation is a result of noticing that the columnar vortex follows the initial counter-clockwise spanwise vortex in every case that it was observed throughout the experiment. The columnar vortex is also much less organized than the counter-clockwise vortex; this would make sense if the vortex was produced with the wave. By the time it is seen in the field of view, it is quite old and has had time to dissipate its energy. It also seems logical that a span-wise vortex would develop across the length of the breaking wave and create an approximate shape of the letter “U” as it impinges onto the bottom of the flume. The “arms” of the “U” shaped
vortex would be created last as the wave breaks first in the middle and continues to roll over until it reaches the sides or the “arms” of the “U” shape. By the time the “arms are developed, the center part of the vortex loop would have impinged upon the bottom and would be moving forward with the direction of the water velocity. The “arms” would have been pulled down with the center of the vortex, where the wave initially started to break, and in some cases, the ends seem to break off to create the columnar vortices like the one observed in this specific case.
Figure 4.32 Image sequence showing sediment suspensions within the column vortex. From top to bottom: frames 2670 (left), 2672 (right), 2674, 2676, 2678, and 2680.
Figure 4.33 The measured velocity field shown in the XZ plane at Y=-67, and the iso-surface, represented by the blue color, showing the vorticity at $\omega_{mag}= 30$ s$^{-1}$. The sediment particles are represented by the red spheres.
4.9 Case 9 Test 11 Image 5300-5360: Strong columnar vortex impinging on bottom.

In this wave event, a breaking wave impinged on the bottom near the onshore side of the measurement volume in frame 5329. A counter-clockwise vortex resulting from the wave was produced, but it was obscured by the entrained air bubbles. The impact of the counter-clockwise vortex did not produce a visible sediment cloud. This is likely due to the absence of bottom sediment in the impingement area. The flow reversed from onshore to offshore in frame 5337. After the flow reversal, a small sediment cloud was stirred up in Frame 5340 by a columnar vortex. The sediment cloud grew in size as the vortex was moved offshore by the seaward mean flow and left the field of view after frame 5346. Figure 4.34 shows the raw images taken from the top camera of the series of frames showing sediment cloud trapped by the columnar vortex.

Figure 4.35 shows the formation of the columnar vortex. The plots include the measured velocity field at Y=-68 mm; the bottom is located at Y = -72 mm. Also plotted are the iso-surface of the Y-vorticity and the distribution of suspended sediment represented by the red spheres. It seems likely that the flow structure captured is a portion of a vortex loop. In this case, the vortex loop impinged onto the bottom of the measurement volume, and a part broke off and produced a columnar vortex that moved in the direction of the water velocity. In Frame 5329, the vortex loop had just hit the bottom and moved offshore. In Frame 5336, the vortex loop has already broken up into two columnar vortices. The counter-clockwise vortex is about to leave the measurement volume, but the flow reversal brings the vortex back into the measurement volume where it begins to pick up bottom sediment. The lower pressure in the vortex core keeps the suspended sediment trapped in the vortex. Some suspended sediment is carried by the
swirling fluid to the top of the measurement volume 40 to 50 mm above the bed. In Frame 5340, the mean flow changed direction and the counter-clockwise vortex was moving along the near side of the measurement volume from onshore to offshore. The columnar vortex did not suspend much sediment until frame 5342 as the direction of the water velocity is changed. The suspended sediment was quickly trapped in the vortex and moved with the vortex offshore.

Figure 4.36 shows a plan view of the above process with plots corresponding to the same frames. The turbulent velocity field is shown at a height $Y=-68$ mm along with contours showing the turbulent shear stress. The sediment is represented by red spheres up to a height of $Y=-63$ mm. The turbulent shear stress observed in Figure 4.36 is essentially a product of the turbulent kinetic energy and the turbulent vertical velocity. For reference, the critical shear stress for initiation of a sand grain of 0.25 mm diameter is around 2.5 cm$^2$/s$^2$. The contours show that the shear stress is one to two orders of magnitude greater than the critical shear stress necessary to mobilize the sediment particle. High turbulent shear stress implies high bed shear stress; these values are related though are not the same because not all fluid momentum is transferred to the bottom. Based on the magnitude of the turbulent shear stress occurring in this event, it is likely that the bed shear stress resulting from the high turbulent shear stress would be strong enough to mobilize the sediment. This can also be seen by observing the regions that experience the high turbulent shear stress in the plots.
Figure 4.34 Sediment entrainment by a columnar vortex. From top to bottom: frames 5328 (left), 5329 (right); 5340, 5342; 5344, 5346. The images are from the right camera.
Figure 4.35 Sediment entrainment by a columnar vortex. The velocity field is shown at $Y= -68$ mm. The iso-surface of vorticity in the vertical ($Y$) direction in s$^{-1}$ correspond to the columnar vortex.
Figure 4.36 Sediment entrainment by a columnar vortex. The turbulent shear stress ($\tau_{turbulent}$) in cm$^2$/s$^2$ is shown at $Y = -68$ mm. The suspended sediment is shown from the bottom of the measurement volume to $Y=-63$ mm.
5. Discussion of Results

In this chapter, the two-phase flow measurements presented in Chapter 4 are compared to the findings of previous studies to discuss the mechanism of sediment suspension and transport by the large eddies induced by breaking waves. The results from different experiment runs are pieced together to provide a more complete picture of the interaction of the large eddies with the sediment.

A great advantage of the V3V technique is the capability to simultaneously measure sediment particle position with the three-dimensional fluid velocity field. Due to limitations in the hardware and software, not all the sediment particles in the flow field can be identified. Therefore, the V3V measurements can only provide relative measurements of suspended sediment concentration. Furthermore, the technique used for phase separation cannot isolate the tracer particles from the flow field. Hence, the fluid velocity field was determined from the motion of both the sediment particles and fluid tracers. This produces some uncertainty in the velocity measurements in regions of high sediment concentration. However, it was shown in Chapter 3 that the phase separation technique can identify sediment particles reliably by filtering out virtually all the tracer particles in the velocity field. Thus, this experiment has produced a unique data set. The sediment suspension process by coherent turbulence was directly observed in a relatively large measurement volume, and the distribution of the suspended sediment can be correlated to the measured flow properties to examine the interaction between the two phases. The flow properties that were investigated include the horizontal velocity and vertical velocity, turbulent kinetic energy, total shear stress, turbulent shear stress, and vorticity.
The vertical velocity was found to be a key component in the suspension and distribution of sediment. In regions of high-suspended sediment concentrations, the instantaneous vertical velocity of the fluid exceeded the sediment fall velocity. The latter is about 0.033 m/s. Mobilized sediment was carried away from the bed in the upward flow around the impingement zone and in the upwash induced by large transverse vortices. The heuristic model proposed by Dean (1973) used a dimensionless sediment fall velocity to predict the cross-shore transport direction. Dean (1973) found that the wave conditions are erosional if the wave-height-to-wavelength ratio in deep water, $H_0/L_0$ is greater than $1.7 \pi w/gT$, where $w$ is the sediment fall velocity and $T$ is the wave period.

The effect of sediment fall velocity on beach transformation is thus directly linked to the vertical velocity of the moving fluid. Sediment particles that can stay in suspension for a long time compared with the wave period would be carried offshore by the undertow. The role of the vertical velocity is also manifested in the vertical distribution of suspended sediment, where the fall velocity is commonly used as a velocity scale in determining the sediment diffusivity (Aagaard and Jensen, 2013). The relationship between mean flow and turbulence in breaking waves and its implication on the direction of net sediment transport was further discussed in LeClaire and Ting (2017).

Vertical velocity is also an important component of the apparent shear stress. The latter includes the turbulent shear stress induced by the turbulence velocities, or the total shear stress when the effect of the mean flow is included. Aagaard and Hughes (2010) concluded that the turbulence resulting from breaking waves can reach the bed and produces an increase in the local shear stresses. LeClaire (2016) and LeClaire and Ting (2017) found high suspended sediment concentrations in the near-bed regions with large
apparent shear stresses. This present study also found that high sediment concentrations were usually found with high total shear stress or turbulent shear stress (see Cases 6 and 7) near the bed.

None of the cases studied in this thesis showed a strong relationship between turbulent kinetic energy (excluding cases with vortices) and sediment suspension. This does not mean that the relationship does not exist, but it does indicate that other flow quantities such as vertical velocity, total and turbulent shear stress, and vorticity may be better parameters for quantifying the effect of breaking waves on sediment suspension under the plunging regular waves studied in this experiment. LeClaire and Ting (2017) found that suspended sediment concentrations do not have a strong relationship with turbulent kinetic energy without the presence of a strong vortex; they noted that the vortex in that case would be the primary source of turbulence energy existing in the flow field.

Horizontal velocity is important in addition to the vertical velocity in that it forms part of the total and turbulent shear stress. Several cases observed that strong horizontal velocity was present in areas that experienced sediment suspension; however, sediment suspension did not occur in situations where there was a strong horizontal velocity but no vertical velocity. Case 6 showed sediment being transported through the measurement volume when the vertical velocity was less than the fall velocity. This can be explained by other reasons, the first is that though the vertical velocity is less than the fall velocity, it will still slow the settling of the sediment. The second reason is that each event can only be seen for a very short time frame, usually less than a few seconds, so the sediment
that was suspended previously will not have had enough time to settle out of the water by the time the vertical velocity is decreased to less than the fall velocity.

Case 2, Case 3, and Case 5 present results from a breaking wave event that produced a large counterclockwise vortex. These cases show a strong relationship between the areas where the vortex impinged on the bottom and the areas that experience sediment suspension. Many of the experiments performed using vortex rings highlight the effect these types of vortices have on sediment beds. The results from Johnson (2009) discussed that the wall shear stress increases as a result of the velocities produced by vortices. Johnson explained that sediment suspension occurs when the vertical drag, typically a result from the turbulent eddies, on the particle exceeds the particle’s immersed weight. Other vortex ring studies such as those performed by Bethke and Kalziel (2012) and Munro et al. (2009), came to similar conclusions. What this study and other studies have shown is that the impact of vortices on an area with sediment will produce high apparent shear stress and vertical velocity which are both conductive to sediment mobilization and transport.

Case 2 shows sediment suspension that is transported high into the field of view well past the boundary-layer depth. Pederson et al. (1995) developed a 2D simulation of plunging waves which modeled suspension within the boundary layer as a diffusion process, and the transport of the sediment by the velocity field as a convection process. Aagaard and Jensen (2013) described that large breakers from plunging waves typically create vertical mixing through a convective process. Munro et al. (2009) clarified that for small sediments the lift force produced from the boundary shear will not affect the particles after they have risen past the boundary-layer depth; Munro et al. commented
that any rise past that depth is a result of the particles’ inertia and the vertical component of the fluid velocity. All of the above studies including this present study show that sediment can be suspended to greater heights by externally generated coherent turbulence than could normally result from boundary-layer turbulence.

Case 9 examined an event that produced strong turbulent shear stress near the bottom of the flume. The case also discussed the difference between turbulent shear stress and bed shear stress. Though not all turbulent shear stress is transferred into bed shear stress, the two values do relate. In case 9, the turbulent shear stress induced by the breaking wave was one to two orders of magnitude higher than the critical shear stress needed to mobilize the particles. Furthermore, this event showed a strong correlation between turbulent shear stress and sediment suspension. These results support the notion that bed shear stress is an important parameter in sediment mobilization.

Case 1, Case 8, and Case 9 show breaking wave events that contain a columnar vortex. In both columnar and transverse vortices the pressure would be lower inside the vortex. The difference is that the axis of rotation is vertical in the columnar vortex while it is horizontal in the transverse vortex. The transverse vortices are much stronger and thus have higher tangential velocities. Sediment particles that have acquired large inertia from the vortex can be spun out into the mean flow; this can be seen in many of the cases that experiences a strong counter-clockwise vortex.

Case 4 shows a unique clockwise vortex that resulted from the rollup of the shear layers. This case shows a clear view of the initial sediment suspension resulting from the splash from the breaking wave. In most cases, this type of event could not be seen because of obstructions from entrained air. The sediment was suspended directly in front
of the clockwise vortex and some sediment was trapped inside, but almost no sediment was lifted behind the vortex. The structure appeared to dissipate quickly for neither the structure nor the sediment cloud was observed after the flow reversal before the next wave.
6. Conclusions

The following conclusions can be drawn from this study:

1. The sediment particles were separated from the tracer particles based on particle radius, intensity, percent overlap, and search tolerances. The phase separation was performed using the Insight V3V software by adjusting the image processing parameters and comparing the detected particles with the particles seen on the raw images. The parameters were validated through several image sets including image sets with tracer particles only; the process showed that over 98% of the tracer particles were removed by the filter.

2. The camera was positioned so that the field of view would capture more breaking wave events while minimizing the interference from entrained air bubbles and side wall effects. The camera was mounted at different horizontal and vertical positions. The line of sight from each sensor and the camera’s reference plane were used to determine the camera’s optimal position.

3. White hollow glass spheres with a mean diameter of 54 microns and a specific gravity of 1.05 were used as tracer particles to represent the fluid. The sediment particles were solid glass spheres ranging in size from 0.212 to 0.25 mm with a specific gravity of 2.5. Flat sheets of sandpaper were glued to the surface of a false bottom to create surface roughness comparable to the diameter of the sediment particles.

4. A still-water test was performed by allowing 20 minutes for the water in the flume to settle down before the images were acquired. The test was used to determine the uncertainty in the velocity measurements. The measured velocities in the X
and Y directions had a mean uncertainty value of 4 mm/s, and in the Z direction had a mean uncertainty value of 3 cm/s.

5. Sediment suspension was highly correlated to areas that experienced a vertical velocity of at least the sediment’s fall velocity. Multiple wave events showed that without large vertical velocity no sediment suspension could occur.

6. Cases that did not involve the impingement of the vortex but did experience high turbulent kinetic energy did not result in significant sediment suspension. The turbulent kinetic energy had to occur with a vortex to result in sediment suspension.

7. Several cases showed that an impingement of a large transverse vortex can result in sediment getting pushed up from the splash in front of the vortex. Sediment was also entrained behind the vortex. Some sediment was trapped and carried with the vortex as it moves out of the field of view.

8. Sediment particles were observed to be entrained, trapped and transported by columnar vortices.

9. Large shear stress was observed to be an important factor in sediment suspension. The transfer of large turbulent shear stress (fluid momentum flux) to the bottom must create large bed shear stress resulting in the initiation of sediment motion. The turbulent shear stress observed was one to two magnitudes higher than the sediment’s critical shear stress.

10. Some breaking wave events resulted in the sediment suspending far above the boundary-layer depth. The distribution of suspended sediment was observed to be a convective process.
6.1 Suggestions for future work

Several helpful conclusions were drawn from this experiment; however, there is still more to be learned about sediment suspension and transport under breaking waves. This experiment focused on sediment suspension under regular plunging waves. Several other types of waves result in sediment suspension and mobilization that could be studied to gain more understanding of sediment suspension and transport. The field of view for this experiment was limited by the equipment. A larger field of view would allow researchers to see the full vortex structures produced in breaking waves; the larger field of view would also allow the suspended sediment to be tracked for a longer period of time. The addition of a sediment bed would provide an environment more similar to natural conditions. The experimental procedure resulted in uncertainty in the velocity measurements that limited the amount of information that could be obtained near the bottom of the flume where the sediment was initially suspended; future studies could be performed with higher spatial and temporal resolutions to focus on the flow parameters that mobilize the sediment.
7. References


