In situ determination of flocculated suspended material settling velocities and characteristics using a Floc Camera.

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1. ABSTRACT

Estimates of suspended sediment settling are necessary for numerical sediment models, water quality studies, and rehabilitation of coastal ecosystems. Settling of cohesive sediment, which is common in estuaries, is more difficult to quantify than noncohesive sediment because of flocculation. Flocs are composed of an aggregation of finer silts, clays, and organic material. Floc characteristics, such as the diameter, density, porosity, and water content determine floc settling velocities. A floc camera provides the ability to capture the settling velocities and other desired characteristics of individual flocs *in situ*. Water samples taken using a Van Dorn sampler are immediately subsampled using a pipette and transferred to the floc camera. The Perspex settling column is outfitted with a LED backlighting to distinguish flocs. The floc camera's high pixel and temporal resolution allows image analysis software to detect individual flocs and process floc statistics per image. Observed changes in floc location with respect to time presents a way of calculating settling velocities. This work presents results of validation tests with known sediment size distributions and of deployment of the camera during a field study.

2. INTRODUCTION

Sediment deposition in estuaries is needed to sustain estuarine habitats subject to sea-level rise such as tidal marshes. Meanwhile, resuspension of deposited sediment can produce turbid water that affects estuarine ecology. Numerical models used to manage estuaries require estimates of settling velocity to compute deposition. In estuaries, cohesive sediment aggregates to form flocs of varying diameter, density, and settling velocity, which are an unknown function of mineral, hydrodynamic, chemical, and biological factors. Thus, it is important to make local, *in situ* measurements of settling velocities in order to quantify deposition and guide parameterization of numerical models. In this paper, we describe a floc camera that measures diameter and settling velocity of individual flocs *in situ*. We test the applicability of the camera, its accuracy with known particle sizes, and the software that determines settling velocities and size characteristics.

3. METHODS

Floc camera

The floc camera is composed of three main components: a high resolution camera, a telecentric lens, and a settling tube. In addition, this work utilizes Matlab programming software to analyze the images. The high-resolution, 1600 x 1200-pixel CCD camera has a maximum frame rate of 30 Hz, shutter speed of 0.03 s, and pixel size of 6.45 μm. The camera lens is telecentric CCD (2/3 inch) with a 1:1.5 magnification with variable apertures. The working distance for the lens is 87 mm with a maximum distortion of 0.6% and depth of focus of 4 mm.

The settling column was constructed from Perspex at columnar dimension of 100 x 100 x 170 mm. The center of the region of interest (ROI) is 94 mm from the top of the settling column. The area for the ROI is 46.3 mm^2 and the volume is 185.2 mm^3. The settling column is equipped with a compact homogeneous LED backlight that emits a 470 nm wavelength blue light. The emitting area is ~1500 mm^2. The exterior of the column is blanketed in white paper to produce uniform lighting. The camera, lens and column are enclosed in an aluminum case (14.5 x 34 x 19 cm) for protection and stability (Figure 1).

Image acquisition and analysis

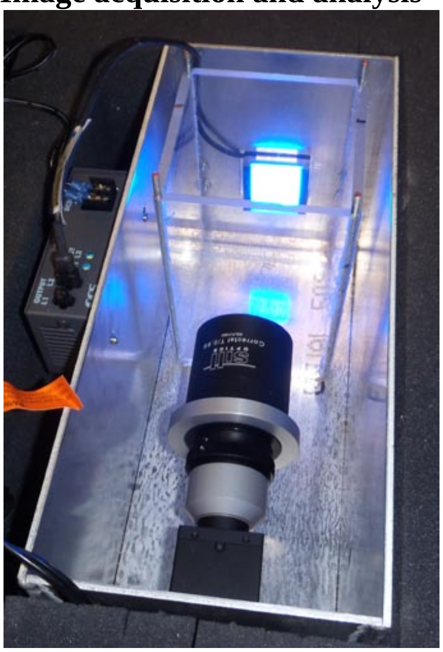


Figure 1. . Image of the floc camera setup.

For field studies, suspended particle samples are collected using a Van Dorn sampler and immediately sub-sampled using a pipet (mouth ID of 6mm and tube OD of 14.5mm) to transfer the sample to the settling column. The pipetted sample is placed carefully in contact with the water surface above the ROI. The wide mouth on the pipette allows the sediment to settle through the pipette into the water column without fluid transfer, thus preventing fluid inertia or turbulence influencing settling velocities (Gratiot and Manning, 2004; Manning et al., 2010). As the particle settle through the ROI a series of images are captured (30Hz images or 7.5Hz video) and saved for image analysis. Images sequences are processed through a series of Matlab software in order to track the settling particles and to capture an accurate size characteristic. These codes are a collaboration of previous code (Larsen et al., 2009a; Larsen et al., 2009b; Lintern and Sills, 2006) in conjunction with new code.

Images are first processed to subtract out the background images (images taken prior to introducing any particles) and images taken with the lens cap on to account for the camera's noise characteristics. Background-subtracted images are further processed through a semi-autonomous sequence of pixel distribution analyzes and then processed through an edge detection algorithm. The edge detection algorithm consists of multi-resolution à trous wavelet decomposition to the N^{th} filter coefficient (Mallat, 1999; Qureshi, 2005). The edge detection algorithm primarily utilizes the two-dimensional discrete wavelet transform. Edge detection is followed by a binary image morphology (dilation followed erosion, see Lintern and Sills, 2006).

The resulting image is binary and defines the boundary of the particles. Binary images are further processed for size characteristics through Matlab's image processing toolbox. Defined particles are then further processed to compute the settling velocity and size characteristics. Mean settling velocity (W_s) and diameter for each floc are determined by identifying the centroid and outline of each floc in a sequence of image frames and tracking individual particles across the sequence. For each sequential pair of images, a match for each floc particle in the subsequent frame is identified as the floc within a search area with the minimum Mahalanobis distance

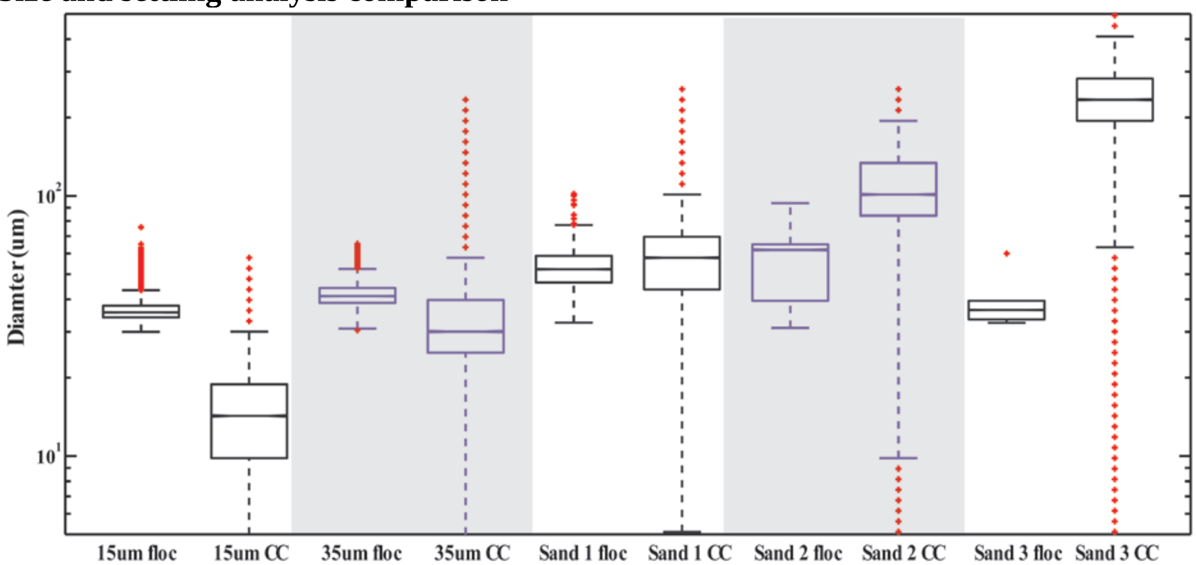
(Mahalanobis, 1936) – a multivariate metric computed from several particle size characteristics (Larsen et al. 2009a).

Size comparison analysis

In order to test the accuracy of the image analysis particle size characterization, particles of a known nominal size were analyzed in a lab environment. In order to test the lower end of the size spectrum, which is influenced more by pixel resolution limits, particles of garnet (density of ~3900 kg/m^3) with a median size of 15 µm (14.93±8.4 µm) and 35 µm (30.07±27.8 µm) were examined. In addition, sand (density of ~2650 kg/m^3) was sieved into several size classes in order to test the higher range. Size classes were: sand 1 57.77±38.8 µm, sand 2 101.1±40.2 µm, and sand 3 234.1±76.1 µm. The sediment was mixed into a solution using deionized H_2O. The solution was then sampled using a pipette and quickly transported to the surface of the settling column surface (filled with deionized H_2O) where several sequences of images were collected for each size class. Material from each size class was then run through a laser diffraction particle size analyzer (LS13 320 Beckman Coulter, Inc.) to compare with the size distributions determined by the floc camera.

4. RESULTS

Size and settling analysis comparison



	15 µm		35 µm		Sand 1		Sand 2		Sand 3	
	Floc	CC	Floc	CC	Floc	CC	Floc	CC	Floc	CC
Mean	36.72	14.93	41.91	37.92	53.88	62.61	57.58	108.09	38.51	246.96
Median	35.65	14.26	41.17	30.07	52.20	57.77	61.97	101.10	36.38	234.07
Min	30.00	0.38	30.44	3.21	32.54	0.38	31.08	0.38	32.54	0.79
Max	75.79	57.77	65.42	234.07	101.80	256.95	93.77	256.95	60.00	541.89
Std	4.44	8.37	5.04	27.83	11.63	38.75	14.58	40.17	8.45	76.10

Figure 2. Size analysis between particles analyzed by the particle sizer (CC) and the floc camera (floc). Vertical lines in the middle of the boxes represent the median, while box top and bottom edges represent the interquartile. Whiskers cover 99.3% of the data and '+' represent outliers.

The floc camera is capable of detecting particles between 35 and 100 µm, but overestimated the median of the 35 µm size class by 11.6 µm. The camera overestimated the median of the 15 µm size class and underestimated that of the sand 2 and 3 size class, with results that were significantly different from those of the laser diffraction particle size analyzer (Figure 3). Distributions of each size class were tested for differences in populations using the Wilcoxon ranksum test and the log base 10 transformation two-sample t-test. Both tests found that the populations determined by the floc camera and particle sizer were different, except for that of sand 1 ($p=0.4$; Figure 2). Settling velocities determined by the camera and velocities calculated by Stokes' law as a function of particle diameter determined by the camera are compared in Figure 3 (Reynolds particle numbers were less than 0.5). Although many of the settling velocities are closely approximated by Stokes' law, some particles fall above the one-to-one line, while smaller particles trend in parallel to the one-to-one line.

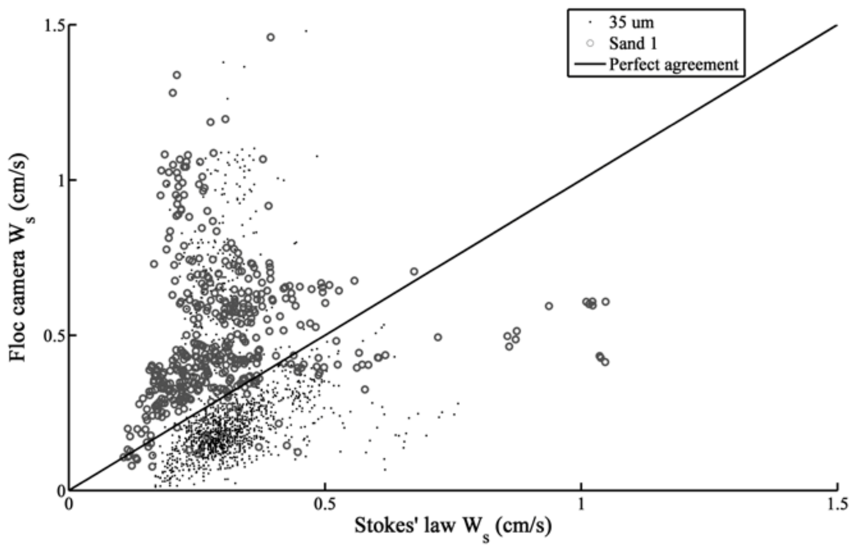


Figure 3. Settling velocities calculated by Stokes' law and settling velocities determined by the floc camera software.

5. DISCUSSION

Accuracy of floc camera in capturing images of settling particles and size characteristics

The floc camera was capable of capturing quality images of particles settling through the column at frame rates of 30Hz. Autonomous image analysis and subsequent autonomous determination of settling velocities and size characteristics are dependent upon an accurate particle detection and location. For this reason it is critical to minimize the external forces that can influence the camera's stability or the fluid during settling. In addition, camera settings such as frame rate and resolution are of equal significance for consistently acquiring a series of quality images.

Accuracy of the floc camera in determining *in situ* settling velocities and size characteristics

Several limitations arise during the image analysis due to the edge detection and the nature of the particles. These limitations can compromise the determination of the particle settling velocities and size characteristics. Results suggest that limits exist at particle sizes less than 15 µm and for translucent particles larger than 125 µm. The accuracy of the camera for smaller opaque particles reached a limit as the diameter of the particle approached ~3-4X the camera's resolution. This limitation resulted in the overestimation of smaller particle diameters (Figure 2). Though this is true for the lower limit because of the pixel size, the inaccuracies at the upper limit was more of a reflection of the material and optics. The silica that the sand was composed of allows some fraction of light through, thereby blurring the edge and creating difficulty in the edge detection algorithm.

In addition to particle translucence, larger settling velocities for larger, faster sand particles create blurring due to the frame rate and shutter speed. Both particle translucence and speed increase the difficulty of detecting edges accurately. These issues are less of a concern when dealing with opaque particles that settle at lower velocities.

Several edge detection algorithms were evaluated for accuracy in particle size determination: the wavelet algorithm used in this work, along with the Canny (1986), Sobel (Farid and Simoncelli, 2004), and Prewitt (Farid and Simoncelli, 2004; Qureshi, 2005) algorithms. The Canny, Sobel, and Prewitt algorithms had deficiencies in detecting edges. The Canny and Prewitt algorithms identified edges as fragmented lines and were therefore unable to delineate the whole floc. The Sobel algorithm was unable to identify the majority of floc particles. The wavelet algorithm detected whole particles and flocs best but at an expense of more user input and computation time. The algorithm requires the user to determine *a priori* the N^{th} filter coefficient, which can be done relatively quickly by running the algorithm on one image.

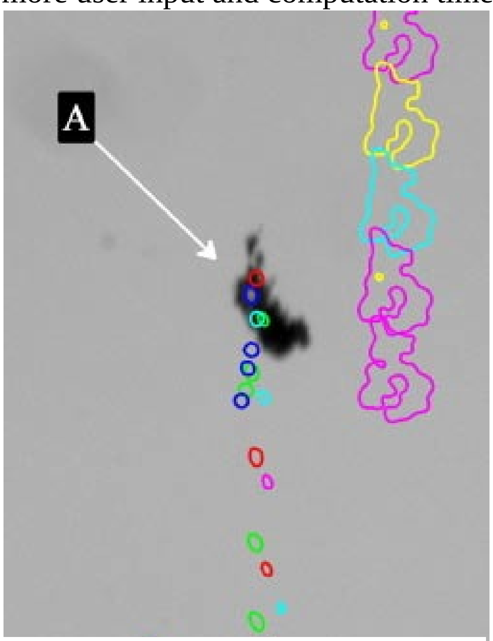


Figure 4. Comparison of edge detection methods for a series of ~15 frames showing the determined particle shapes.

Besides the aforementioned problems with detecting edges, edge detection algorithms can detect ‘particles’ that are a component of a floc, as depicted by Figure 4 (floc). This figure shows a series of detected particles for ~15 frames overlaid on the original image. In this case the edge detection determined a settling velocity that is accurate to a particle of a much larger size, thereby producing outliers or at least a greater range in the correlation between settling velocities and particle size. This could explain some of the outliers in Figure 2 and 3.

The poor correlation between the measured settling velocities and those calculated using Stokes’ law leads to some concern in the accuracy of the software in determining settling velocities. The majority of the velocities fell close to the line of perfect agreement (Figure 3). Data points that run in parallel to the line of perfect agreement may suggest that the density of the material used may be incorrect or may be a resultant of the overestimate of smaller particle diameters. The data points that are significantly off the line of perfect agreement and are not parallel to it suggest that some measured settling velocities may be erroneous. The authors speculate that this may be a function of the software detecting different particles but treating them as the same particle and therefore calculating a distance that a perceived but nonexistent floc traveled per unit time.

6. CONCLUSION

This work has shown how the combination of the floc camera and software can capture and analyze floc settling velocities and size characteristics within certain constraints. Limitations exist within the software and the settling velocities and optical properties of the particles being analyzed. Edge detection algorithms had difficulty identifying translucent edges and edges of small particles that approached the resolution of the camera, while the camera had difficulty capturing large sand particles settling quickly. The autonomous tracking software produces accurate velocities, but a thorough quality analysis should be done. While limitations do exist, this paper has shown that accurate settling velocities and size can be obtained in a semi-autonomous manner. Settling velocities and particle size are critical for modeling sediment deposition and transport. This camera allows for an *in situ* determination of these parameters and can aid in the investigation of the complex questions associated with cohesive sediment transport.

7. ACKNOWLEDGEMENTS

This work would like to acknowledge the support offered by the U.S. Bureau of Reclamation. We would like to offer special thanks towards Dr. Laurel Larsen for her input in this work.

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