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Characterization of Eroded Mud Aggregates with the Flume Imaging Camera System (FICS) and Its Added Value to Sediment Management Projects

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PURPOSE: The goal of this technical note (TN) is to describe the functionality and added research value of the Flume Imaging Camera System (FICS), a US Army Engineer Research and Development Center (ERDC)-developed system designed to measure the size of sediment particles immediately following erosion.

INTRODUCTION: Sediments within a majority of the waterways managed by the US Army Corps of Engineers (USACE) are heterogeneous mixtures of sand, silt and clay. These mixed sediments have the tendency to behave cohesively. When cohesive beds are mobilized, through either natural erosion or dredging activities, sediments tend to be moved as chunks or bed aggregates rather than discrete particles. Individual sand, silt, and clay particles are on order of <63 µm[*] to 2 mm with densities ranging from 2.4 g/cm^3 to 2.8 g/cm^3 (Mehta 2013). Whereas, the density of bed aggregates is similar to the bulk density of the bed (~1.15 g/cm^3 to 1.8 g/cm^3) and sizes can range from 10s of microns to several millimeters (Rust and Nanson 1989; Wright and Marriott 2007; Fettweis et al. 2009; Smith and Friedrichs 2011; Plint et al. 2012; Gastaldo 2013; Perkey et al. 2020). The aggregation state of sediment significantly impacts the size and density of particles and thus alters the transport characteristics of sediments (Smith and Friedrichs 2011; Mehta 2013; Forsberg 2018; Perkey and Smith 2019). A recent study using simple numerical simulations driven by realistic hydrodynamic forcings from the James River estuary found bed aggregates to largely be limited to incipient suspension or bedload transport while disaggregated fines were predominately maintained in suspension (Perkey and Smith 2019).

Differences in transport characteristics (e.g., initiation, mode, frequency) between bed aggregates and disaggregated constituent particles have significant implications for sediment transport management. Understanding and managing sediment transport and deposition processes in the Nation's navigable waterways is a primary mission for the USACE. Mathematical models are commonly used to predict sediment movement for USACE projects concerning channel infilling and beneficial usage of dredged material. Currently, USACE numerical models utilized to predict sediment transport either weakly describe or do not include aggregate properties and transport processes. One particular concern with these current USACE numerical models is the limited or lack of descriptions of aggregate generation, degradation, and transport processes.

[*] For a full list of the spelled-out forms of the units of measure used in this document, please refer to US Government Publishing Office Style Manual, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248-52, *https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf*.

These models commonly rely on size and settling velocity data obtained from a disaggregated sediment sample. The lack of aggregate transport process descriptions in these models could result in misleading estimates of project performance and impact (Perkey and Smith 2019).

Presently, little is known of the abundance or size of fine sediment aggregates that are eroded from the bed. With better representation of these physical properties, more accurate predictions of transport processes may result, which will aid project engineers in making more informed management decisions. The goal of this document is to present a novel approach for characterizing the size of fine sediment aggregates generated thru erosion. The FICS was developed to use in conjunction with an erosion test flume. This TN introduces the FICS, assesses FICS particle sizing routines with particles of known sizes, and presents an example field application.

FLUME IMAGING CAMERA SYSTEM (FICS): The FICS is an ERDC-developed system designed to characterize grain size of sediment particles immediately following mobilization from the bed (Figure 1). The FICS channel attaches directly to the outflow end of the USACE-developed Sedflume (McNeil et al. 1996). The FICS system consists of a clear polycarbonate channel, an Allied Vision Manta G504B camera equipped with an Opto Engineering TC23056 bi-telecentric lens, and a light emitting diode (LED) back light paired with a Pulsar 320 strobe control. The FICS channel measures 22.5 cm × 10 cm × 2 cm. The width (10 cm) and height (2 cm) are the same as the Sedflume Channel. The camera and lens are centrally mounted 12.8 cm above the top of the channel. FICS images capture an area of 4.5 × 5.3 cm with a focal depth of 2.7 cm. Magnification of the system is 0.157x, resulting in a pixel size of ~22 µm. FICS image processing requires particles to appear in an area of at least 3 × 3 pixels (Milligan and Hill 1998; Mikkelsen et al. 2004; Lintern and Sills 2006). The FICS is capable of resolving particles down to ~66 µm while the upper size limit is constrained by the frame size (4.5 × 5.3 cm).

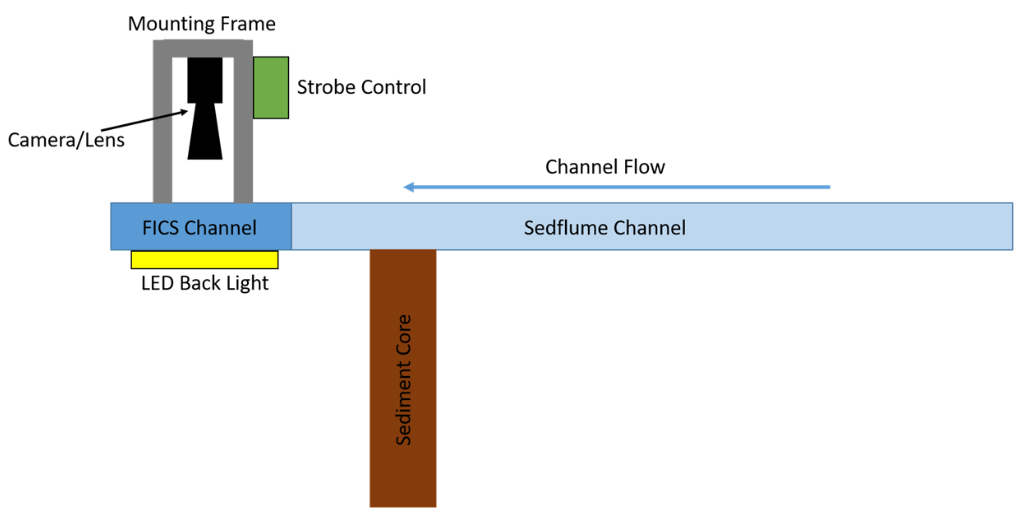

Figure 1. Schematic showing the FICS system mounted to the outflow end of the Sedflume.

The LED light source is positioned opposite of the camera. This backlighting produces a darkened silhouette of the particles against a lighter background (Figure 3). To ensure particles in the image are not blurry due to particle movement, the backlight is strobed with a controller synchronized with camera exposure. StreamPix software is utilized to interface with the camera system to program sampling parameters (exposure rate, gain, strobe pulse rate, sample rate, sample length) and record video files. During initial testing, optimal quality images were collected with an exposure rate of 500 µs, gain of 10, and a 30 µs strobe pulse. FICS can sample at a rate up to 20 frames per second continuously (limited by storage availability) or for a defined set of time. Prior to an experiment, a calibration grid is inserted into the FICS channel within the focal plane and photographed for the purpose of transforming pixel space to length space.

FICS IMAGE ANALYSIS ALGORITHM: An automated image analysis routine was developed to characterize the size of eroded particles in images collected with the FICS. The routine employs algorithms from the MATLAB Image Processing Toolbox. The algorithm consists of three main parts: (1) image processing to identify candidate particles, (2) particle vetting to omit unwanted features such as background objects, air bubbles, and out-of-focus particles, and (3) calculation of particle size distributions. A flow chart describing the algorithm is provided in Figure 2A. A brief description of the routines is presented in the following sections.

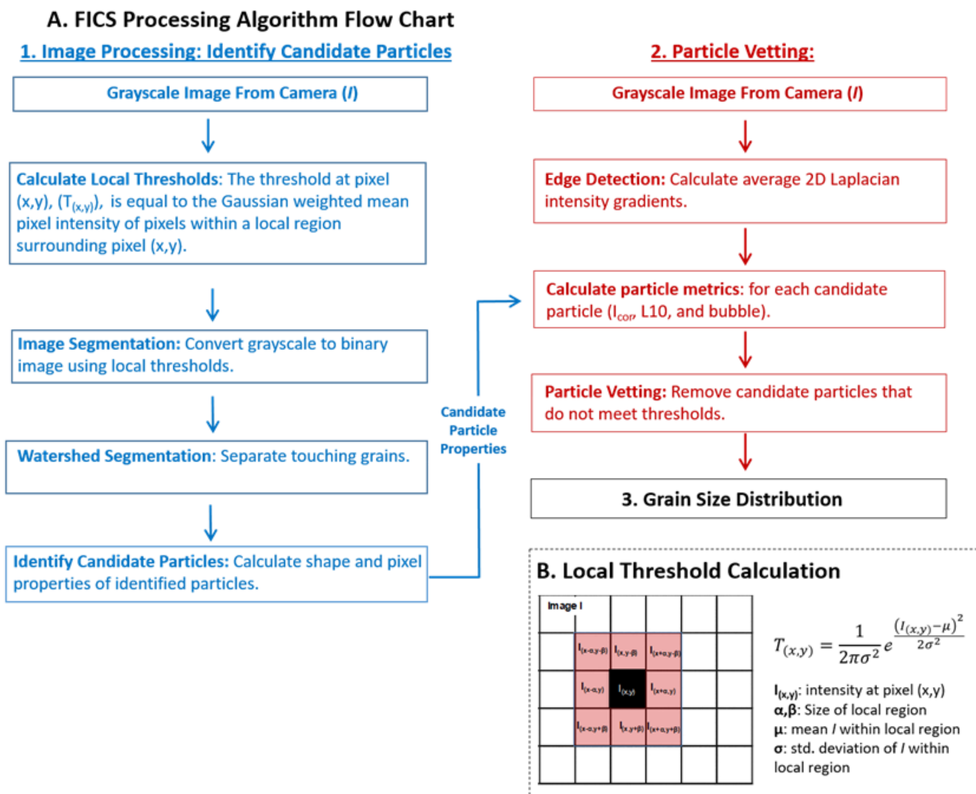

Figure 2. (A) Flow chart of the FICS image-processing algorithm. (B) Simplified schematic of local threshold, T(x,y) calculation for a given pixel (x,y). The example in the schematic assumes a local region or neighborhood size of [3, 3]. FICS uses a local region of approximately 300 × 255 pixels.

IMAGE PROCESSING: FICS images are collected in grayscale (Figure 3) in which each pixel within the image is assigned an 8-bit integer from 0 – 255 that describes the pixel's brightness or intensity. Pixel intensity corresponds to different shades of gray, ranging from black (0) to white (255). The aim of image processing is to generate a binary image from the original grayscale image. Binary images characterize pixels with two intensity values: 0 to denote background and 1 to indicate particle. FICS images are converted to binary images via thresholding. Thresholding is a popular image segmentation method that differentiates particles from background based on pixel intensity ($I_{(x,y)}$) relative to a defined intensity threshold, T (Gonzalez et al. 2004). The FICS image-processing routine determines an appropriate intensity threshold for each pixel using a locally varying threshold function (Figure 2B). The intensity threshold for a given pixel ($T_{(x,y)}$) is defined as the Gaussian weighted mean of the intensities of the pixels within a local region of approximately 300 × 255 pixels surrounding the given pixel. Particles in the FICS appear dark (low intensity) against a light background (high intensity) (Figure 3), so pixels with intensities equal to or less than their respective $T_{(x,y)}$ are marked as particle pixels and assigned "1" ($I_{(x,y)} \leq T_{(x,y)}$). Pixels with intensities greater than corresponding $T_{(x,y)}$ are marked as background pixels and assigned "0" ($I_{(x,y)} > T_{(x,y)}$). On occasion, two or more particles moving close to one another are interpreted as one large, connected particle (Figure 3B). To deal with particle overlap and separate touching grains, the binary image is refined using watershed segmentation (Gonzalez et al. 2004; Graham et al. 2005; Kornilov and Safornov 2018). Finally, position and size metrics (in pixels), for each identified candidate particle, are calculated.

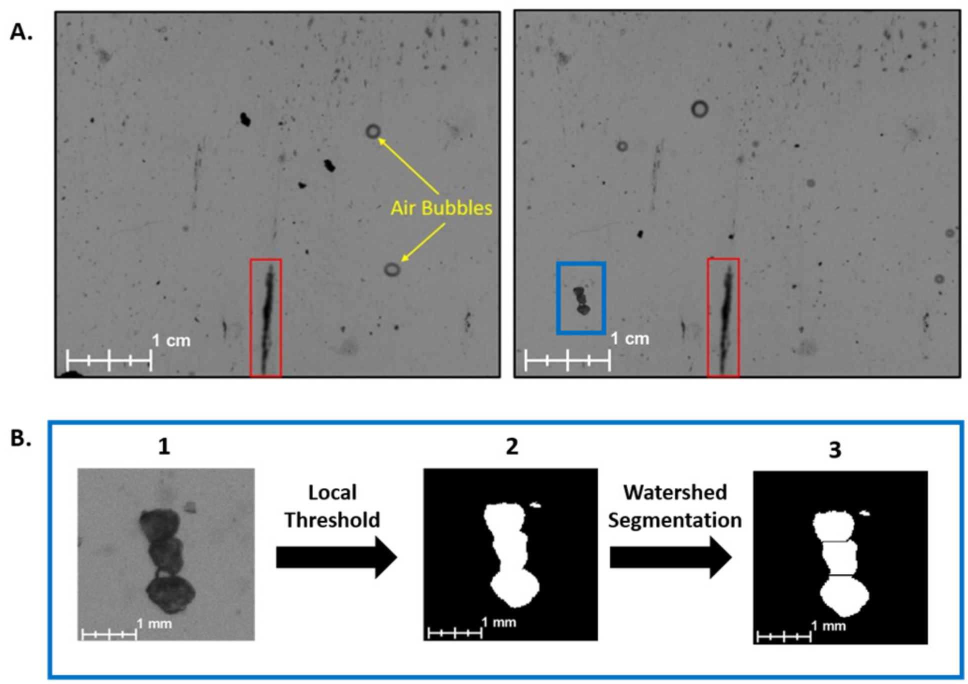

Figure 3. (A) Example of concurrent frames from a FICS video captured during the erosion of a sediment core collected from the James River estuary, Virginia. Red boxes indicate an example streak on the channel wall removed with the correlation threshold filter. Yellow arrows indicate example air bubbles removed with the bubble threshold filter. (B) Basic steps of the image-processing algorithm: First, convert the original grayscale image (1) to a binary image using local thresholding, (2) and then refine the binary image using watershed segmentation to account for touching grains (3).

PARTICLE VETTING: To filter out features such as background objects within the FICS channel (such as scratches or unavoidable streaking during erosion intervals), air bubbles, and out-of-focus particles within the FICS channel, three user-defined thresholds are used: (1) correlation (T_{BKGD}), (2) bubble (T_B), and (3) focus (T_f).

Background Objects (T_{BKGD})**.** Identified features that do not change position in concurrent frames, such as scratch marks or streaks on the channel walls (Figure 3A, red box), are filtered from the data set with the correlation threshold (T_{BKGD}). For each particle, the Pearsons correlation coefficient (I_{Cor}) is calculated between the intensities of the pixels within that particle and the intensities of the pixels in the same location in the previous frame. Particles whose position correlates to the previous frame at a value greater than the user-defined correlation threshold ($I_{Cor}>T_{BKGD}$) are marked as "background" and removed from the data set. A default value for T_{BKGD} is set to 0.4 but can be modified by the user.

Bubbles (T_B)**.** As indicated in Figure 3, bubbles appear as circular objects that are bright in the center (high intensity) and dark around the edges (low intensity). Particles are more uniform in intensity throughout. The ratio between the mean intensity of pixels in the center (I_c)to mean intensity of the pixels around the edge (I_e) is calculated for each identified particle. When the value of this ratio is greater than the user-defined bubble threshold ($I_c/I_e>T_B$), the particle is flagged as a bubble and removed from the data set. An appropriate T_B is usually between 1.0 to 1.1**.**

Out of Focus. Edge detection is used to distinguish between in-focus and out-of-focus particles. Edge detection is a gradient-based method, grounded on the concept that in-focus particles will have sharper gradients in their intensity values at the edges relative to out-of-focus particles. A two-dimensional (2D) Laplacian spatial filter is applied to each grayscale image. For better resolution of edges, the Laplacian gradient values were averaged, yielding a Laplacian-averaged gradient at each pixel ($L_{(x,y)}$). Because the particles in FICS images are dark against a light background (Figure 3), the gradient along particle edges is equal to the subtraction of the high-intensity background pixel from a lower-intensity particle pixel. Therefore, a lower L(x,y) indicates a more prominent and in-focus edge. For each particle, the 10th percentile of the $L_{(x,y)}$ for pixels along its perimeter (L_{10}) was calculated. Particles with L_{10} values less or equal to the user-defined focus threshold ($L_{10}\leq T_f$) are classified as in focus while particles with L_{10} values greater than T_f ($L_{10}>T_f$) are marked as out of focus and removed from the data set. Particles along the edges of the frame are removed to avoid accepting partilces that may be partially out of the field of view.

GRAIN SIZE DISTRIBUTION: FICS image analysis characterizes size of individual particles in terms of the equivalent spherical diameter (esd) or the diameter of a sphere that has the same area as the particle. In grain size applications, it is useful to display results in terms of volume-based size distributions rather than individual particles. For each accepted particle, particle volume (v) is calculated from the esd, $v=(\pi/6)esd^3$. Particle volumes are then binned into particle size class bins to produce a volume-based size distribution. When processing FICS data, the analyst is free to choose the size and limits of the size bins, within its resolvable size range.

EVALUATION: The FICS sizing algorithm was evaluated using two different sand samples of relatively known size ranges. Sieving techniques were used to generate (1) a narrow distribution of very fine sand (63–125 µm) and (2) a wide distribution of very fine to coarse sand (63–1000 µm).

Each sample was continuously introduced through a port on top of the Sedflume channel. Water was pumped through the flume at a rate of approximately 96.5 L/min, and five videos were recorded as the sample was transported through the imaged region. The image processing routine was used to process each video. Results from all the videos were composited and used to calculate an average volume based distribution (Figure 4B).

For comparison, volume-based particle size distributions of both samples were measured using Laser Diffraction Particle-Size Analysis (LDPSA). Laser diffraction is based on the principle that a spherical particle of a known size scatters light forward in a manner that is predictable in that the scattering angle is inversely proportional to the particle diameter (Agrawal and Pottsmith 2000). LDPSA was performed using a Malvern Panalytical Mastersizer 2000. Results are presented as a volume-based particle size distribution over 100 logarithmically spaced bins from 0.02 µm to 2 mm (Figure 4A). To compare the two instruments, FICS particle size bins were chosen to match and extend the Malvern size class bins. FICS particle volumes were binned into 48 logarithmically spaced size bins from 63 µm to 16 mm (~1/6 ϕ). The two instruments overlapped from 63µm to 2 mm.

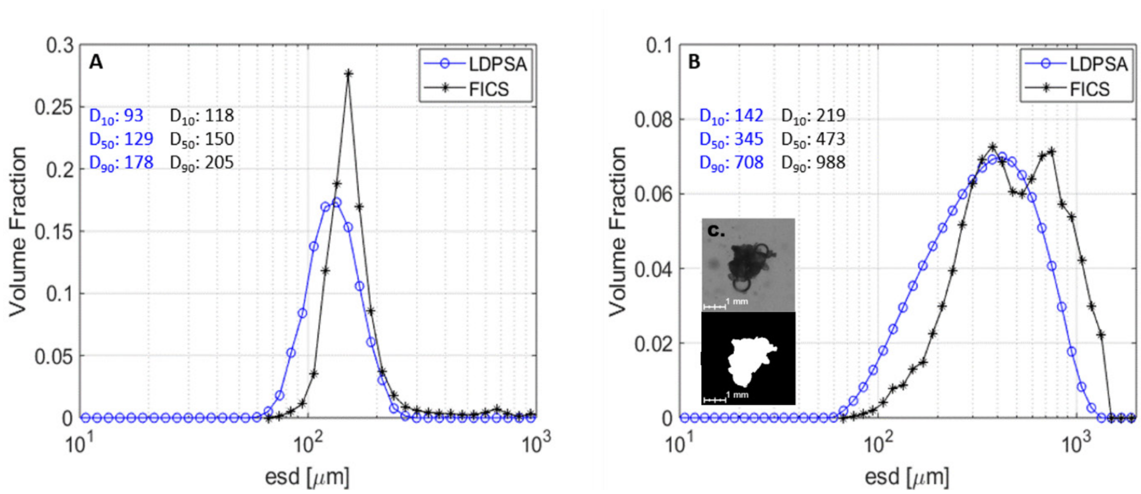

Figure 4. Comparison of FICS and LDPSA size distributions of the two test sands. (A) very fine sand (63 – 125 µm) and (B) very fine to coarse sand (63 – 1000 µm). (C) Example of a clump of sand grains that they were not discernable enough from one another to be appropriately separated. The greyscale image is on top, and resulting binary image after watershed segmentation is on bottom.

Results showed that both methods produced distributions that sized particles beyond the upper bounds of the sieve distribution (Figure 4). Previous studies have documented coarser distribution results in LDPSA and image analysis results when compared to sieve data (e.g., Konert and Vandenberghe 1997; Sime and Ferguson 2003; Graham et al. 2005; Blott and Pye 2006). Differences between sieve data, LDPSA, and image analysis are not surprising as each method determines size differently. With sieving, size is based upon the minimum particle axis while LDPSA and image analysis report distributions based on assuming an esd. For LDPSA, size distributions are interpreted from the scattering pattern produced by the particles in suspension using theoretical models (e.g., Mie or Fraunhofer) that assume spherical particles (Agrawal and Pottsmith 2000; Xu and Guida 2003). Image analysis resolves individual particles and estimates esd from the 2D projected area (Sime and Ferguson, 2003; Li et al. 2005). A direct comparison between the FICS and LDPSA data showed that in general the size distributions were similar for both types of sand evaluated (Figure 4). FICS distributions were consistently found to be slightly coarser with D_{10}, D_{50}, and D_{90} values consistently being 1.2 – 1.5 times larger than LDPSA values (Figure 4A). Image analysis often results in coarser, narrower distributions compared to LDPSA (Xu and Guida 2003; Li et al. 2005). A direct 1:1 relationship of FICS data to LDPSA data should not be expected given the differences between laser diffraction and image analysis (Mikkelsen et al. 2005; Li et al. 2005; Agrawal et al. 2008; Smith and Friedrichs 2011). Review of FICS images showed periodic clumping of sand grains within the flume that likely partially contributed to a coarser distribution data generated by the FICS (Figure 4C). Despite best processing efforts, the sand grains were not discernable enough from one another to be accurately separated. However, overall, results from the evaluation indicate that FICS system is a reliable method for characterizing particle size and distributions are comparable to those obtained through LDPSA methods.

FIELD APPLICATION: The FICS was used to evaluate the aggregation state of eroded sediment from cores collected from a routinely dredged navigation channel within the James River estuary, VA (Perkey et al. 2020). Many dredging projects within the James River estuary place material in channel adjacent disposal areas (within ~500 m). The presence of eroded mud aggregates and their impact on sediment transport pathways was a concern for infilling of the nearby channel. The FICS application in the James River provided key insights about sediment dynamics of the system. Bed aggregates were commonly observed during erosion (Figure 5C), across a range of shear stresses, indicating that high energy conditions were not required to erode and transport bed aggregates. Comparisons were made between disaggregated grain size distributions of the sediment bed (Figure 5A) and FICS-based size distributions obtained during erosion testing (Figure 5B). The size properties were quite different for particles eroded as aggregates versus in their disaggregated constituents (Figure 5). LDPSA distributions (Figure 5A) showed a median grain size (D_{50L}) of approximately 15 μm, and less than 4% of the total volume was attributed to particles >100 μm. By comparison, 100 % of the total measured particle volume was attributed to clasts > 100 μm in the FICS distributions and median grain sizes (D_{50F}) were approximately 100 times greater than the corresponding disaggregated medians obtained through LDPSA (Figure 5). Observations from this study are guiding efforts to incorporate aggregate properties observed with the FICS into sediment transport modeling being done with the USACE Geophysical Scale Transport Modeling System in the James River.

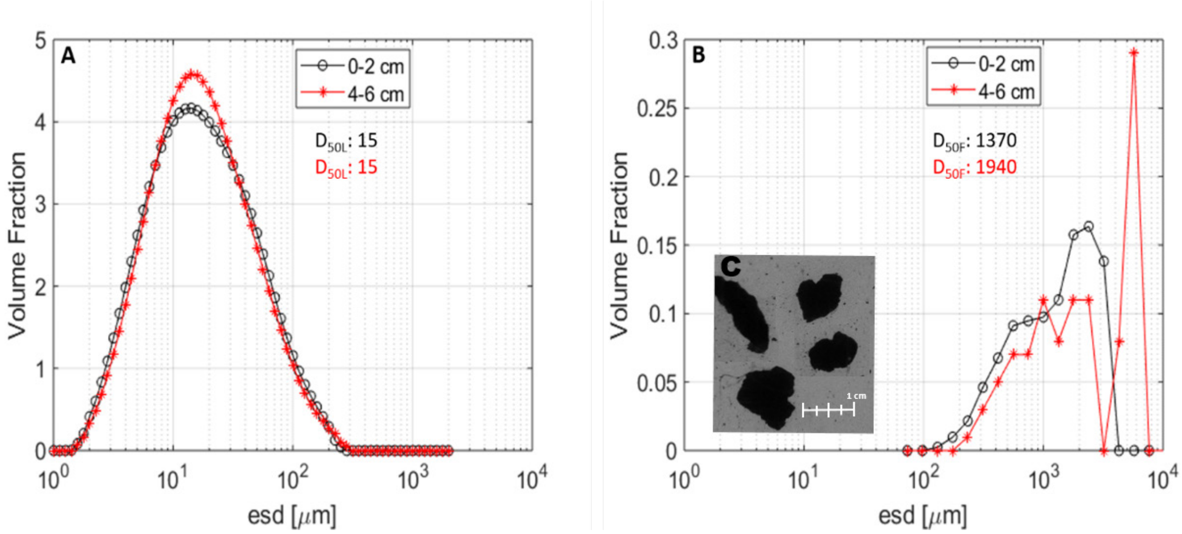

Figure 5. Example of results from a field study utilizing the FICS. (A) Disaggregated (LDPSA) and (B) Aggregated (FICS) size distributions from a core collected from within the navigation channel of the James River estuary, Virginia. The example displays the results of erosion at two depths down core. The associated shear stress applied during the collection of these FICS distributions was 0.5 and 1.0 Pa for the upper and lower sample, respectively. (C) Example bed aggregates ~1 cm esd observed by FICS during erosion testing.

SUMMARY: The majority of sediments within the waterways managed by the USACE are a heterogeneous mixture of sand, silt, and clay that can produce bed aggregates when mobilized from the bed through natural processes or dredging activities. The mobility and transport modes of mixed sediment beds are significantly influenced by the aggregation state of the particles, yet limited observations are available that characterize fine sediment aggregate erosion and transport. Because of this, current numerical models that predict sediment movement for USACE projects either weakly describe or do not include aggregate properties and transport processes. The lack of aggregate transport process descriptions in these models could result in misleading estimates of project performance and impact. The FICS was developed to provide insight on the abundance and size of fine sediment bed aggregates being mobilized from the bed thru erosion.

The FICS is designed to be utilized in conjunction with the USACE-developed Sedflume and collects images of particles following erosion from the bed. An automated image-analysis routine characterizes the size of eroded particles. The routine combines local intensity thresholding with particle vetting to accurately identify particles while omitting unwanted features such as background objects, air bubbles, and out-of-focus particles. The FICS is capable of resolving particles down to ~66 μm. The ability of the FICS to accurately identify and size particles was evaluated using two different sand samples of relatively known size ranges. Results from the evaluation indicate that FICS accurately characterizes particle size and produces distributions that are comparable to those obtained through laser diffraction methods.

The FICS camera system was used to evaluate the size and aggregation state of eroded sediment from cores collected from a routinely dredged navigation channel within the James River estuary, Virginia. Results showed that the sediment bed was mostly composed of fines (<63 μm), but erosion predominately occurred in the form of bed aggregates that ranged in size from 100s of microns to a few millimeters. Observations from this study are driving work to incorporate the aggregate properties into USACE numerical sediment transport models.

While this is just one example, it establishes the importance of aggregate processes within USACE-managed systems and demonstrates the benefits of the FICS in aggregate research. To maintain the Nation's ports and channels, the USACE expends approximately $1.4 billion annually and removes $>1.4 \times 10^8$ m^3 of material in dredging activities (USACE 2016). Discerning the sediment sources and transport mechanisms that lead to infilling is therefore a crucial component to effectively managing sediment within the Nation's waterways. The potential importance of sediment aggregates extends beyond channel infilling. Beneficial placement of dredge material is a major regional sediment management strategy of the USACE to aid in storm protection, land creation, and environmental restoration projects. Successful application of strategic placement requires understanding of fate or transport characteristics of placed sediments. FICS provides vital information to characterize fine sediment transport following erosion. With better representation of these physical properties, more accurate predictions of transport processes may result. These refined predictions will aid project engineers in making more informed management decisions.

ADDITIONAL INFORMATION: This ERDC TN was prepared by Kelsey Fall (*Kelsey.A.Fall@usace.army.mil*), David Perkey (*David.Perkey@usace.army.mil*), and Jarrell Smith (*Jarrell.Smith@usace.army.mil*), ERDC. The study is funded by the USACE Dredging Operations and Environmental Research Program. This TN should be cited as follows:

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