

SAND PARTICLE SIZE ANALYSIS BY SEDIMAGING IN A FIELD LAB

G. Horstmeier[1], J. Eykholt[2], C. Kempf[3], A. Ventola[4], R. Hryciw[5]

ABSTRACT

SedImaging is an innovative alternative particle size analysis method developed to obtain high-resolution particle size distributions (PSDs) of sands. It was developed at the University of Michigan (UM) and is based on wet processing and digital image analyses of fine to medium sands. This work summarizes a variant of the SedImaging method, named FieldSed, which was first applied in a field lab setting for a sediments site by the authors and colleagues in October 2017. The goal of this work was to detect subtle variations in the fine sand and fines compositions as a pilot test at a field laboratory, without use of a sieve set or oven drying. The testing program included replicates, independent testing by UM, and other quality control measures. Sediment processing included wet-removal of fines and particles larger than coarse sand; preparation of the sample in a pre-sorter tube followed by sedimentation in a tall, water-filled column to sort the sands; and the collection and analysis of high-resolution digital imagery of the settled sand. The FieldSed method included variations to estimate mass percentages of oversized (> 2 millimeters [mm]) and undersized (< 0.075 mm) sediments, and throughput improvement. Wet sieving and air drying were used to separate and prepare oversized sediments for weighing. Multiple decants of sediment-water mixtures were used to wash out more dispersive fines. Decanted fines contents were estimated by differences in wet weights and by specific gravity approximations. Digital images were analyzed and used to generate high-resolution PSDs, which typically included more than 80 size bins from 2 mm to less than 0.050 mm. The FieldSed method was successful in clearly distinguishing coarse and fine material, as well as defining the gradient between medium sands, fine sands, and coarse silts. Color, angularity, and other grain characteristics from the digital imagery were noted. With further testing to improve processing rates and efficiencies, the method could be applied to provide same-day field decisions. More efficient and faster processing could be achieved for characterization of cleaner sands, and applications could be expanded further, such as to assess suitability of post-dredge sand cover materials in the field.

Keywords: innovative technology, grain size, image analysis, sediment bedforms, contaminated sediment.

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INTRODUCTION

As part of a geoenvironmental investigation of a river site, sediment samples were collected and analyzed. The goal of the testing program was to rapidly obtain accurate particle size distributions (PSDs) and support detailed mapping of fine sediment bedforms. The testing and analysis were performed using the first field application of SedImaging (short for sediment imaging) method developed at the University of Michigan (UM) for particle size analysis based on wet processing and digital image analyses of fine to medium sands (Ohm and Hryciw 2014). The digital image is analyzed by wavelet transform algorithms, and the computed particle sizes are sorted from largest to smallest to form a volume-based PSD. Ventola and Hryciw (2019) developed FieldSed (Figure 1), a lightweight field-portable version of the hardware for SedImaging. The results and method are also detailed in Ventola, et al. (2020). The field method does not require ovens or a sieve set and eliminates the need to ship specimens to distant geotechnical or analytical laboratories. Therefore, FieldSed can provide high-resolution PSDs of sands within hours of sample collection.

Although sieve and hydrometer testing is common, other alternatives exist to obtain PSDs. Chadwick and Arias (2014) demonstrated an in-situ friction-sound probe for characterization of sediments in San Diego Bay and a sand cap pilot study in the Anacostia River in Washington, DC. This cone-based technology is based on the principle that, as a cone penetrometer is advanced into sediment at a controlled speed, friction sound (acoustic energy) intensity is proportional to the grain size of the particles in contact with the cone. The friction sound probe amplitudes were lower for fine sands and silts, and the amplitudes were greater for coarser sands. The system requires a hydraulic ram on a heavy frame to advance the cone at a steady rate, but it can be used to quickly distinguish different sands (fine, medium, coarse) with vertical resolution (grain-size depth profiles). Laboratory testing of grab samples is also used for calibration, within the method. The two main limitations of the method are lower resolution for PSDs and vessel and rigging requirements to use the cone technology. Other techniques may include electrical resistivity geophysical surveys (sands and gravels are typically more electrically resistive than fine sands, silts, and clays) and digital photography analysis techniques for characterizing streambed particle sizes (Buscombe, 2013).

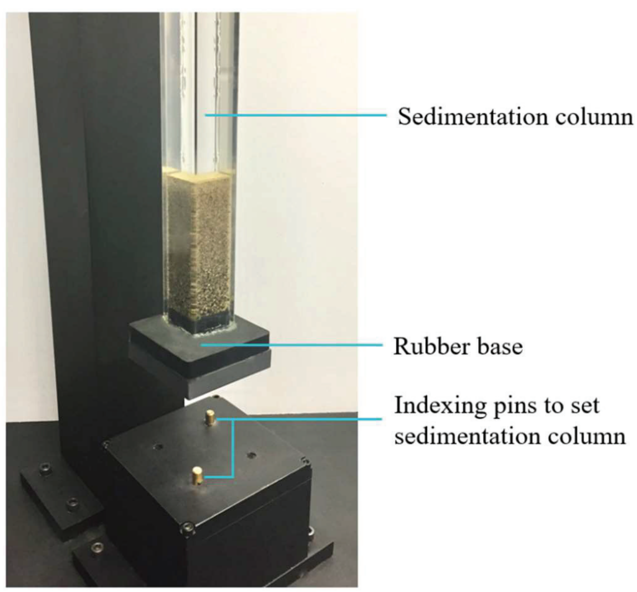


Figure 1. FieldSed device at imaging station.

SedImaging has the advantage of providing high-resolution PSDs from grab sample, because fines and oversize materials that may interfere with image analysis are screened out with preprocessing steps, and sands are sorted by sedimentation prior to imaging. Results from processing the high-resolution digital image can yield hundreds of size 'bins' and the digital image can also be analyzed for color, porosity, angularity, and other features (Zheng and Hryciw 2016a and 2016b). SedImaging is an ex-situ technique and, therefore, less sensitive to site access or the method of sampling.

SedImaging methods, including the FieldSed method, have been shown to have excellent agreement with sieve analysis for sands (Ohm and Hryciw, 2014; Ventola, et al. 2020). Coarse particles (> 2 mm) can be imaged but, for the field version of this method, are not efficiently separated for the selected sedimentation column length and cross-sectional area and, therefore, are removed with a pre-screening step. Fines, with diameters less than 0.075 mm (75 micrometers), need to be largely removed as the camera magnification is not set high enough for their characterization. Fines removal is accomplished by preparatory steps and, for cleaner sands (e.g., < 5% fines), can be accomplished simply by the sedimentation process without preprocessing. For quantification of percent fines, an approximate method is provided in Ventola et al. (2020) and summarized below. While particles as fine as 40 micrometers may be imaged, the general method is not targeted to characterize fines. The method could be coupled with other technologies in the future to collect and analyze fines, perhaps with other optical methods, passive sampling vessels, or by filtering and extractions/digestions of fines for chemical analyses.

The FieldSed technology is available for additional studies through Prof. Roman Hryciw and Andrea Ventola, at the Department of Civil and Environmental Engineering, University of Michigan in Ann Arbor, Michigan. More recent developments have also included changes to the sedimentation column and imaging method, as well as other steps to refine the method.

METHODS

SedImaging was originally developed for the analysis of sands (Ohm and Hryciw 2014); however, the method has been modified to allow for the analysis of sediment with fines. The main steps of SedImaging are: 1) field pre-processing, including preparing a sample for the sedimentation column; 2) image collection; and 3) generation of PSDs. Methods for SedImaging and its field implementation, FieldSed, are described more completely in Ventola, et al. (2020), and the FieldSed method is summarized below.

For the first application of the FieldSed technology (Eykholt, et al. 2019, Ventola and Hryciw 2019), sediment cores were collected and transported to the field processing station. The FieldSed laboratory (Figure 2) was enclosed and had electricity and water but was without temperature control. Sediment samples were selected for SedImaging by staff geologists. Most samples were selected to distinguish between samples described as "sands [without fines]" (< 5% fines), "sands with silt/clay" (5-12% fines) and "silty/clayey sands" (12-49% fines), or to more carefully examine fines content. In the field, visual inspection alone makes it difficult to distinguish the wide gradient between sands [without fines] and sandy silts. Eighty sediment samples were analyzed in eight field days.

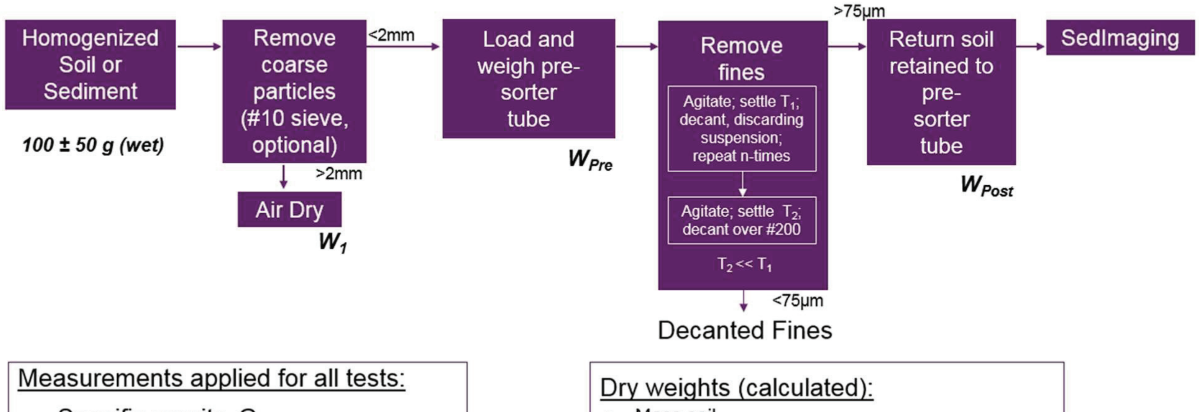
Wood staff completed the pre-processing and digital image collection in the on-site field laboratory. The digital images were sent electronically to the UM where the images were analyzed, and PSDs were generated. However, no computer limitations prevented the analysis of images at the field lab. The final PSDs were adjusted by considering the mass fraction of coarse sand (> 2 millimeters [mm]) and gravel material and decanted fines (< 0.075 mm) found during sample pre-processing. UM also analyzed replicates to evaluate the repeatability of the FieldSed test and the agreement of the results with traditional sieving.

Figure 2. FieldSed field laboratory.

Field Pre-Processing

First, coarse sands and gravel were removed (if present). Samples were then sieved using a #10 (2 mm aperture) sieve. The portion retained on the sieve was air dried and weighed (W_1) with a bench top digital scale. The portion passing the sieve was loaded into a pre-sorter tube. Once the sediment sample was loaded, water was added to a pre-set mark on the tube, and the tube mass (W_{pre}) was recorded.

The next step involves removing dispersive fines from the material in the pre-sorter tube. The sediment was mixed, and the suspensions allowed to settle for set times (T_1 and T_2). Most particles remaining in suspension were decanted as waste. After the suspension settles, multiple decants were usually required to achieve a relatively clear suspension. The first set of decants were performed with a settling time of 2 minutes (T_1 = 2 minutes), which was long enough for fine sand-sized particles to settle, but quick enough for the more dispersive fines to remain in suspension. The final decant was performed after a settling time of 30 seconds (T_2 = 30 seconds), which was quick enough to decant most dispersive fines while retaining sands and some coarse silts. The suspension was poured over a #200 sieve (0.075 mm aperture). Sand collected on the sieve was returned to the pre-sorter tube. The pre-sorter tube was filled again with water to the pre-set mark, and the mass (W_{post}) and number of decants was recorded. A diagram of the pre-processing procedure is shown on Figure 3. Figure 4 shows an example of a sample in the pre-sorter tube before and after decanting fines (left and right images, respectively).



$$W_{2+3} = \frac{G_S * (W_{Pre} - W_{EW})}{G_S - 1}$$

$$W_3 = W_{2+3} - \frac{G_S * (W_{Post} - W_{EW})}{G_S - 1}$$

Figure 3. Flowchart for pre-processing procedure.

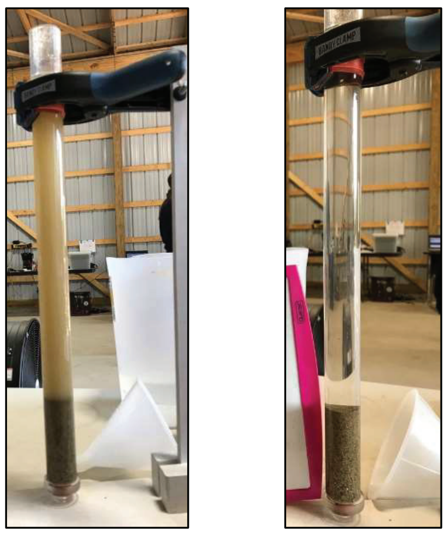


Figure 4. Sample in pre-sorter tube before (left) and after (right) decanting fines.

The method uses measurements on a wet mass basis to determine the fines percentage, but it is a differential method that assesses the loss of fines from the bulk sand (rather than a direct measurement of the mass of fines). Fines were intentionally removed from the imaged fractions but not lost in the process. Fines were collected and delivered to process wastes. To reduce the volume of process wastes, process water was recycled by filtration, stored in containers marked as non-potable, and reused for FieldSed tests.

Mass measurements are noted on the process diagram (Figure 3), where W values refer to mass (grams), not weight. Measurements include the mass of air-dried solids retained on the #10 sieve (W_1), and masses of the filled pre-sorter tube before and after decanting fines (W_{pre} and W_{post}, respectively). The mass of the pre-sorter tube, without sediment, filled with water to a standardized height (pre-set mark) is W_{EW}. Other than air-drying, which was necessary for the portion retained on the #10 sieve, no sample drying was required. Instead, dry weights were calculated with field measurements and an assumption for specific gravity (G_s). For these test results, the specific gravity was assumed to be 2.55 based on previous specific gravity measurements of site sands. The water temperature was recorded for each test to allow a density correction for dry weight calculations.

After pre-processing, samples were loaded into the sedimentation column. A rubber balloon was used to seal the open end of the pre-sorter tube. The balloon was deflated before being attached to establish a slight vacuum seal, the tube was inverted, and the sediment and water fell to the balloon-sealed end. The balloon was carefully removed, and the vacuum held the sediment and water in the column. The pre-sorter tube was placed over a settling column into a connector (a circular tube connected to a square column adapter), and the vacuum was released by removing a stopper on the top of the tube.

With the stopper removed and the vacuum released, the sediment fell into the water-filled settling column. Larger particles settled faster than finer particles. This size segregation is central to the method because the digital image analysis is much more accurate when nearby particles have similar sizes. Most settling occurred within 2 minutes, but the columns were typically left for hours before the images were collected.

The settling columns, constructed of clear acrylic measuring 6 feet by 1 inch by 1 inch, were mounted in a rack (Figure 2). Care was taken to make sure the columns were secured and mounted vertically.

Imagery

Columns with settled sediment were moved to a separate assembly for imaging. The assembly locks one column in place and sets a specified distance from a high-resolution camera. The outer surface of the column was wiped clean to remove dust. The camera was focused on the few inches of settled sand, and its distance was adjusted forward or backward if a desired focal length was needed. Further details are discussed in Ventola, et al. (2020).

Digital imagery was collected two or four times (i.e., on either 2 or 4 sides of the column). Collecting four-side imagery generally improved accuracy (as PSDs are determined from averages) but collecting two-side imagery improved throughput. The final digital image sets were reviewed, saved, and electronically sent to UM for analysis. On-site image analysis was possible, however, if a more rapid analysis was needed.

PSD Generation

The UM team analyzed the images offsite using a computer algorithm for volume distribution, on a flexible schedule. The UM lab provided cropped digital images and unadjusted PSD values for the imaged fraction of the sediment samples. Unadjusted PSD outputs from the computer analyses were high resolution: hundreds of percent passing value bins for diameters ranging from 0.040 mm (40 micrometers) to 2 mm. The PSD results from each image (side of column) were numerically averaged at each size bin to generate a composited PSD (result).

Wood analyzed the unadjusted PSDs to complete the analysis and reporting. Two percent passing values, calculated from masses as shown on Figure 3, were used to adjust computer-generated PSD values into a PSD that considers oversized (> 2 mm) and undersized (< 0.075 mm) materials. The percent of decanted fines was calculated by the following equation:

$$P_{DF} = \left(\frac{W_3}{W_1 + W_{2+3}}\right) \quad (1)$$

The percent finer than 2 mm was calculated by the following equation:

$$PP_{2mm} = \left(\frac{W_{2+3}}{W_1 + W_{2+3}}\right) \tag{2}$$

In this analysis, the adjusted PSD value (PP_{adj}) was calculated by the following equation:

$$PP_{adj} = P_{DF} + \left(\frac{PP_{2mm} - P_{DF}}{100\%}\right)(PP_{raw}) \tag{3}$$

where:

PP_{adj} = percent passing value, adjusted to consider oversized and undersized materials
P_{DF} = percent of decanted fines
PP_{2mm} = percent finer than 2 mm
PP_{raw} = percent passing value from raw, computer-generated PSD, calculated from analysis of digital images.

Further details on the adjusted PSD calculations, with an example, are presented in Ventola, et al. (2020).

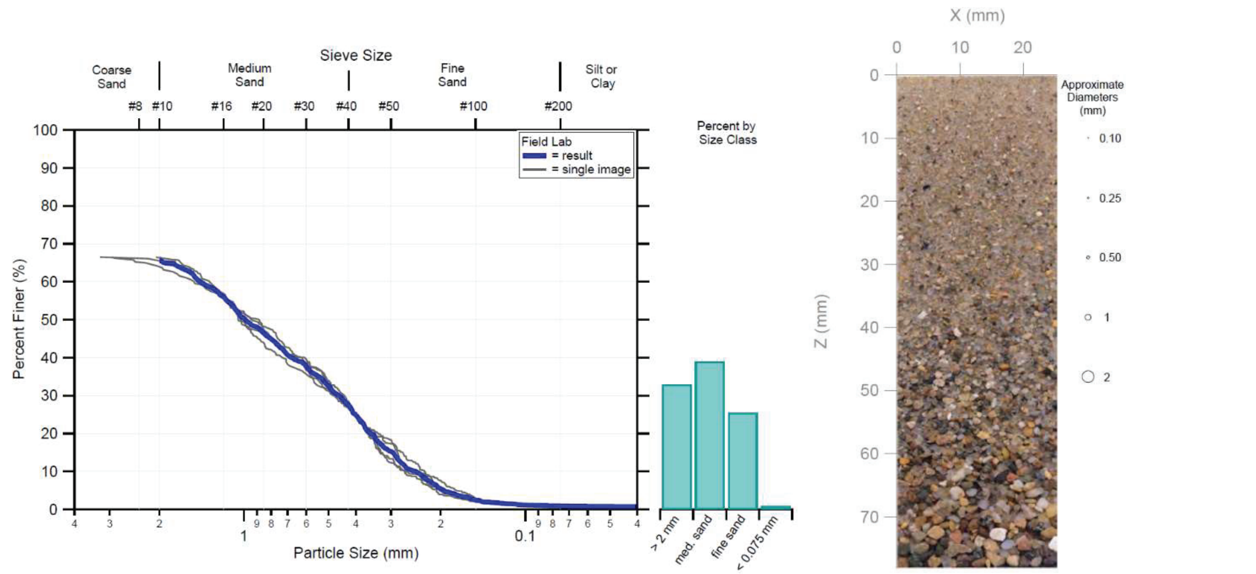
RESULTS

Samples tested ranged from 0 inches to 72 inches below the sediment-water interface in the following intervals, with interval frequency usually decreased with depth:

- Interval 1 from 0 to 6 inches
- Interval 2 from 6 to 12 inches
- Interval 3 from 12 to 24 inches
- Continuing in 12-inch intervals

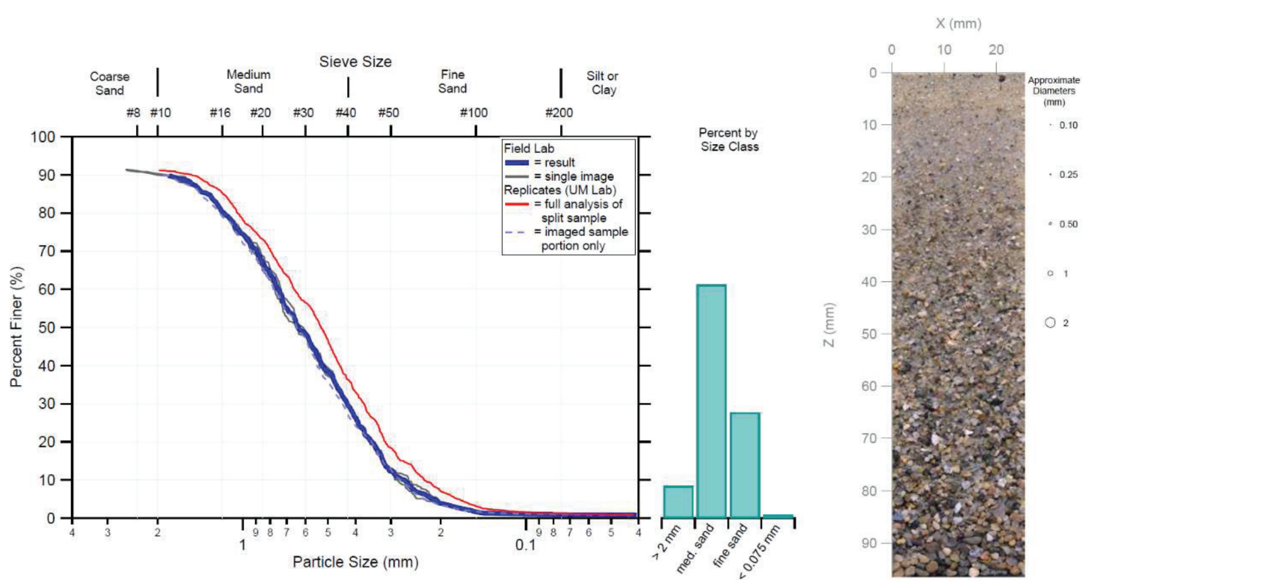
Of the samples imaged, 43 samples were sands with trace (< 5%) fines, 18 samples were sands with 5-12% fines, 18 samples were silty sands with > 12% fines, and one sample was silt (> 50% fines). Numerous sand types were analyzed and there is a large spread in the dataset. For example, the coarse sand fraction ranged from 32-100% passing the #10 sieve (2 mm). The fines fraction ranged from 0-61% passing the #200 sieve (0.075 mm). Grading also varied. Of the 43 sands with trace fines, 32 samples were poorly graded and 11 samples were well graded. Of the 18 sands with 5-12% fines, 14 sands were poorly graded and 4 samples were well graded.

Representative examples are show in Figure 5, Figure 6, and Figure 7. Note that the values reported in the boxes below the image and PSD are of the composited PSD (result).



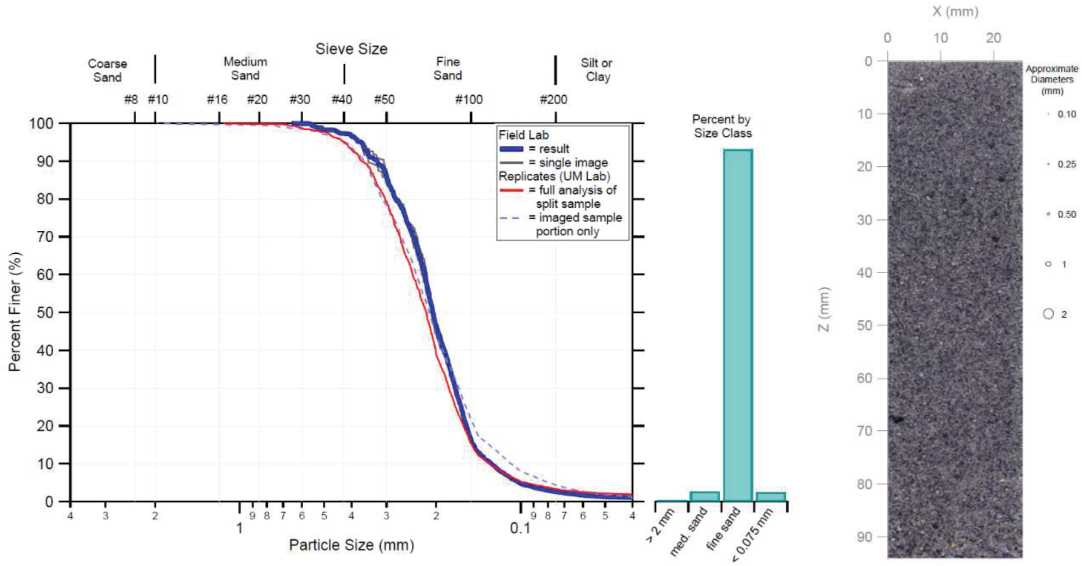
Effective Diameters (mm)		Coefficients	Summary of Particle Size Distribution		
D_{10}: 0.25	D_{50}: 0.99	C_u: 5.8	< 2 mm	= 65.6%	medium sand or finer
D_{20}: 0.36	D_{60}: 1.43	C_c: 0.6	< 0.420 mm	= 26.9%	fine sand or finer
D_{30}: 0.46	D_{80}:		< 0.075 mm	= 0.9%	fines, total
				= 0.2%	fines, as imaged
				= 0.8%	fines, decanted

Figure 5. Example 1 – grain size summary from FieldSed analysis.



Effective Diameters (mm)		Coefficients	Summary of Particle Size Distribution		
D_{10}: 0.27	D_{50}: 0.64	C_u: 2.8	< 2 mm	= 90.2%	medium sand or finer
D_{20}: 0.35	D_{60}: 0.75	C_c: 0.9	< 0.420 mm	= 29.2%	fine sand or finer
D_{30}: 0.43	D_{80}: 1.16		< 0.075 mm	= 0.9%	fines, total
				= 0.1%	fines, as imaged
				= 0.9%	fines, decanted

Figure 6. Example 2 – grain size summary from FieldSed analysis.



Effective Diameters (mm)		Coefficients	Summary of Particle Size Distribution		
D_{10}: 0.13	D_{50}: 0.21	C_u: 1.7	< 2 mm	= 100.0%	medium sand or finer
D_{20}: 0.16	D_{60}: 0.22	C_c: 1.1	< 0.420 mm	= 97.3%	fine sand or finer
D_{30}: 0.17	D_{80}: 0.28		< 0.075 mm	= 2.6%	fines, total
				= 1.5%	fines, as imaged
				= 1.1%	fines, decanted

Figure 7. Example 3 – grain size summary from FieldSed analysis.

Replicate Analysis

Two types of replicates were analyzed by the UM lab. The first type was for samples that were already pre-processed, imaged, recovered from the settling column, and re-bagged. Five replicates of this type were used to test variations from the camera being operated in a different environment and by different operators. The second type was for split samples requiring pre-processing and imaging. Six samples of this type were meant to test variations in pre-processing and imaging. Analyses conducted at UM were performed independently.

As shown in Figure 6 and Figure 7 for two representative samples, results of replicate analyses show strong agreement with parent samples. Minor variations are attributed to a small number of coarse particles shifting the curve, but the curves' shapes and locations are approximately equal. These results suggest a high level of reproducibility.

Bedform Application

Environmental contamination in sediments generally follows fine-grained sediments. While contaminant concentrations are often reliably low in coarse-grained sediments, there is a higher probability of variable contaminant concentrations (including non-detect concentrations) in fine-grained sediments. Efficient measurements of fines and sand characteristics are important for site characterization, and field lab determinations may be helpful for promoting adaptive sampling decisions. Therefore, a stratified sampling plan, in which sampling density is higher in fine-grained sediment beds, is beneficial.

To inform the stratified sampling plan, individual sediment bedforms were mapped along the surface of the riverbed using bathymetry data collected in November 2016 and April 2017. In a riverine (non-impounded lake) section, these individual bedforms were grouped for sampling purposes into either coarse-grained bedforms in the main channel (coarse group) or fine-grained bedforms in likely depositional areas (fines group), typically off or along the edges of the main channel. In addition to the bathymetric evaluations, the bedform classifications were further refined using gradation data and statistical analysis of physical characteristics.

At the sediment site, FieldSed-tested grain sizes for samples were collected along one stretch of the river, including an impounded lake area. Of the samples imaged, 26 samples were in the impounded lake and 54 samples were in the channelized flow. This dataset was combined with other grain size results, of which samples were tested via lab-based SedImaging, sieve, and hydrometer.

In the impounded lake, 323 total sediment gradation samples were collected. These samples were selected to be representative of the impounded lake both spatially and with depth. In general, the impounded lake has a variety of grain sizes, with most grain-size samples classified as silty fine sands or silts. The impounded lake has more varied surficial sediment gradation, but clear patterns exist. The main channel and side channels contain coarser surface sediment, whereas channel edges, mouth bars, and backwaters consist of finer surface sediment. Subsurface sediments throughout most of the impounded lake tend to be heterogenous with depth. Median particle diameters (determined from each sample's PSD) were consistently fine sand or silt, with two exceptions that were medium sand.

In the riverine section, 239 total sediment gradation samples were collected. In general, the coarse bedform group with 62 grain size samples contained sands and, to a lesser extent, sands with silt. Gravels and fine-grained sediment were significantly less frequent. In general, the fines bedform group, with 177 grain-size samples, contained silty sands and silts, and to a lesser extent contained gravels. With this fines group, there is a wide range in gradation but with a noticeable tendency toward fine sands and silts. The statistical-based sampling design for the analytical sampling program was well-supported by the effective bedform classifications, and reliable estimates were achieved for surface-weighted average concentrations and other contaminant concentration trends by bedform.

CONCLUSIONS

In summary, FieldSed played an important role for refining bedform classifications and quantifying grain size variations in sediment reaches. Bedform-based groupings of sediments, supported by physical features of grain-size, bathymetry, and geomorphic classifications, were an effective way to reduce overall uncertainty in average contaminant concentrations and concentration variance by reach.

Although the SedImaging method is not a standard particle size analysis method, many benefits exist that are not afforded to sieve and hydrometer testing. SedImaging offers a high resolution, quantitative field laboratory measurement of PSD with an especially well-defined gradient between coarse sand and coarse silt particle sizes. Visual inspection alone makes it difficult to distinguish the wide gradient between sediments classified as sand [without fines] and sediments classified as sandy silt. FieldSed reduces the uncertainty of sediment classifications based solely on visual inspection. Time and money savings are possible because SedImaging does not require oven drying or shipment of samples to an off-site laboratory. Multiple sedimentation columns in parallel can increase testing throughput. Further refinements and automations, some currently being developed at UM, are increasing throughput and quality of the PSDs. Further analytical options of the high-resolution digital imagery present unique opportunities. For example, color, roundness, angularity, porosity of particles may be summarized from the imagery.

Further application of FieldSed is encouraged for the analysis of sands and sandy sediments. For example, dredge passes can be improved with higher resolution, rapidly obtained grain size data. This is especially applicable when physical data are paired with chemical analytical data for residual management decisions. In addition to the goal of achieving high-resolution PSDs for sandy sediments (the goal of this work), the technology should be highly proficient for checking the suitability of post-dredge sand cover materials, understanding differences between upstream river sands and runoff of fill-sands, or for the detection of urban debris (plastics, glass, and other debris).

The FieldSed method is targeted to the analysis of sandy sediments, although approximations for percent fines were achieved in a practical manner. FieldSed analysis of clayey and silty sediments is technically possible, but more time-consuming and inefficient for low sand contents. The current FieldSed method generates fines as a separate waste stream that is not analyzed. However, for sandy sediments with significant fines, the overall utility of the FieldSed method might be improved if it were also coupled with separations and analysis methods for the fines. Unlike standard hydrometer methods which use chemical dispersants or high-energy mixing (e.g., waring blender), fines analyses coupled with FieldSed could be more representative and practical.

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CITATION

Horstmeier, G., Eykholt, J., Kempf, C., Ventola, A., and Hryciw, R. "Sand Particle Size Analysis by SedImaging in a Field Lab," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Virtual Meeting & Awards, USA*, June 15-17, 2021.

DATA AVAILABILITY

Some data used during the study are available from the corresponding author by request. Some data or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.