Particle Size Distribution of Kalamazoo River Sediments by FieldSed

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Abstract: The FieldSed is an inexpensive portable device for performing an image-based soil particle size analysis. The process, which includes the image analysis, is referred to as SedImaging (short for sediment imaging). The FieldSed was used for an investigation of Kalamazoo River sediments to generate over 100 particle size distributions (PSDs). Core samples taken from the river were tested in a nearby field lab. When necessary, samples were processed prior to testing in the FieldSed to remove particles greater than 2.0 mm and those finer than 0.075 mm. Doing so was necessary to ensure the efficiency of the current SedImaging method. A small number of specimens was selected for quality control testing to determine the reproducibility of SedImaging results. This testing also involved sieve analyses in ascertaining the agreement between SedImaging and sieving results. The control test results presented in this paper demonstrate that the FieldSed is a promising device that can rapidly, accurately, and repeatedly determine particle size distributions in field labs for geotechnical and geoenvironmental applications. **DOI: 10.1061/(ASCE)GT.1943-5606.0002421.**

Introduction

As part of a geoenvironmental investigation of the Kalamazoo River in Southwest Michigan (Fig. 1), river sediment samples were collected and analyzed to map river bedforms. The goal of the testing program was to rapidly obtain accurate particle size distributions (PSDs) to delineate areas for more detailed subsequent mapping of fine sediment bedforms in the Kalamazoo River. To this end, the testing and analysis were performed using the first field application of Ohm and Hryciw's (2014) SedImaging (short for sediment imaging) method for a particle size analysis. A field laboratory, shown in Fig. 2, was established near the Kalamazoo River for the program. The laboratory was enclosed and had electricity and water but was without temperature control or an oven to dry the soil specimens. Over 100 collected sediment core samples were tested to determine their PSDs. The soils consisted mostly of fine sands with varying percentages of silt and clay.

The field laboratory utilized new portable hardware for SedImaging. Known as the FieldSed, the system prepares soil specimens for photographing and their ensuing image-based particle size analysis. The field method does not require ovens or sieve shakers and eliminates the need to ship specimens to distant geotechnical or analytical commercial laboratories. As such, FieldSed can provide PSDs of sands within hours of a sample collection. This paper describes the FieldSed system and presents typical results of the field tests and additional highly controlled tests performed at the University of Michigan (UM) on a select number of Kalamazoo River sediment specimens. The additional testing at UM was used to evaluate the repeatability of the FieldSed test and the agreement of the results with traditional sieving.

FieldSed System

SedImaging involves sedimenting a soil specimen through a column of water to sort the particles by size and photographing the deposited soil column. An image analysis then produces the specimen's PSD. Ohm and Hryciw (2014) showed that SedImaging is an efficient alternative to a sieve analysis. However, the laboratory hardware used by Ohm and Hryciw for SedImaging—in this study referred to as LabSed—is large, heavy, and practically immobile. Therefore, Ventola and Hryciw (2019) developed FieldSed, a lightweight field-portable version of the hardware for SedImaging.

Fig. 3 shows the FieldSed system and the location of the camera relative to the soil column. A captured image of the soil is analyzed incrementally using an algorithm based on the Haar wavelet transform (HWT). Unlike many image analysis techniques (Buscombe 2008; Tutumluer et al. 2000; Graham et al. 2005; Kozakiewicz 2018; Masad and Button 2000; Kuo and Frost 1996; Nie et al. 2015; Guida et al. 2017), the HWT method does not size each soil particle individually. Instead, the HWT method analyzes the spatial distribution of pixel greyscale intensities within small 256 × 256 pixel subareas of the image. A particle size for each subarea is determined using a universal calibration between a sieve-defined particle size and a wavelet index defined by Shin and Hryciw (2004). Thousands of areas in the image are analyzed, and the computed particle sizes are sorted from largest to smallest to form a volume-based PSD. Hryciw et al. (2015) detail the HWT image analysis method for particle sizing and generating PSDs.

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Fig. 1. Kalamazoo River and the project's testing locations. (Map data © 2020 Google, Image Landsat/Copernicus, Image NOAA.)

Fig. 2. Field laboratory for testing the Kalamazoo River sediments.

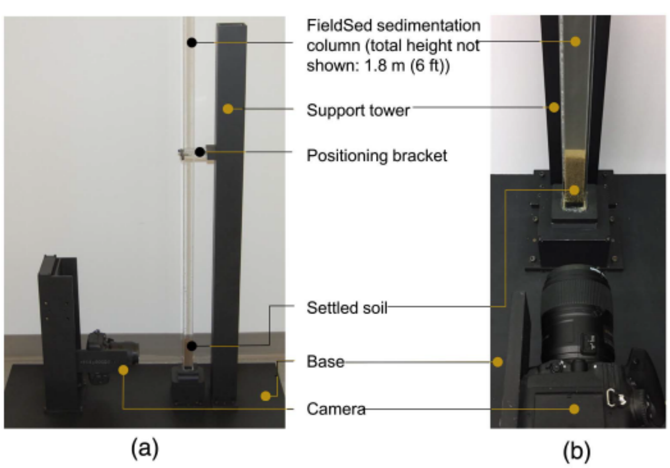

Fig. 3. FieldSed: (a) side view; and (b) front view. (Reprinted from Ventola and Hryciw 2019, © ASCE.)

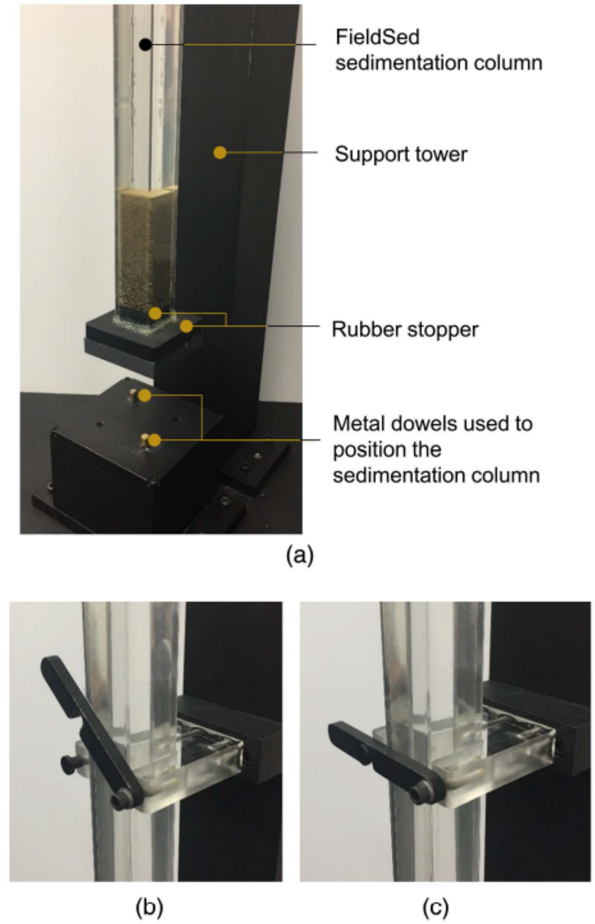

Fig. 4. FieldSed components: (a) base and positioning dowels; (b) positioning bracket unlocked; and (c) locked. (Reprinted from Ventola and Hryciw 2019, © ASCE.)

The analysis is the same for images collected by FieldSed as it is for LabSed.

A comparison of the LabSed and FieldSed hardware was provided by Ventola and Hryciw (2019), so only the most important FieldSed details are presented in this study. The system consists of a lightweight water-filled 25 mm × 25 mm × 1.8 m (1 in. × 1 in. × 6 ft) transparent acrylic sedimentation column. The column is sealed at its base by a square-sectioned hard rubber stopper. The stopper rests on the aluminum base shown in Fig. 4(a). The column's verticality is ensured by two 6 mm (0.2 in.) diameter metal dowels protruding upward from the base [Fig. 4(a)] and the U-shaped positioning bracket shown in Figs. 4(b and c). The rubber stopper has four precisely machined holes on its underside to accommodate the metal dowels. The entire column containing soil and water can be manually rotated in 90° increments after unlocking the bracket and lifting the column off the dowels. As such, all four sides of a sedimented soil may be photographed.

A soil specimen is introduced into the top of the sedimentation column using a 25 mm (1 in.) diameter, 455 mm (18 in.) long acrylic cylindrical presorter tube [Fig. 5(a)]. The purpose of the presorter tube is to break up any soil clumps that may be present in the soil as well as to instantaneously release the specimen into the sedimentation column. If necessary, the presorter may also be used in a prewashing step, which will be discussed subsequently in this paper. The presorter is open on one end and has a vacuum quick-release plug on the other.

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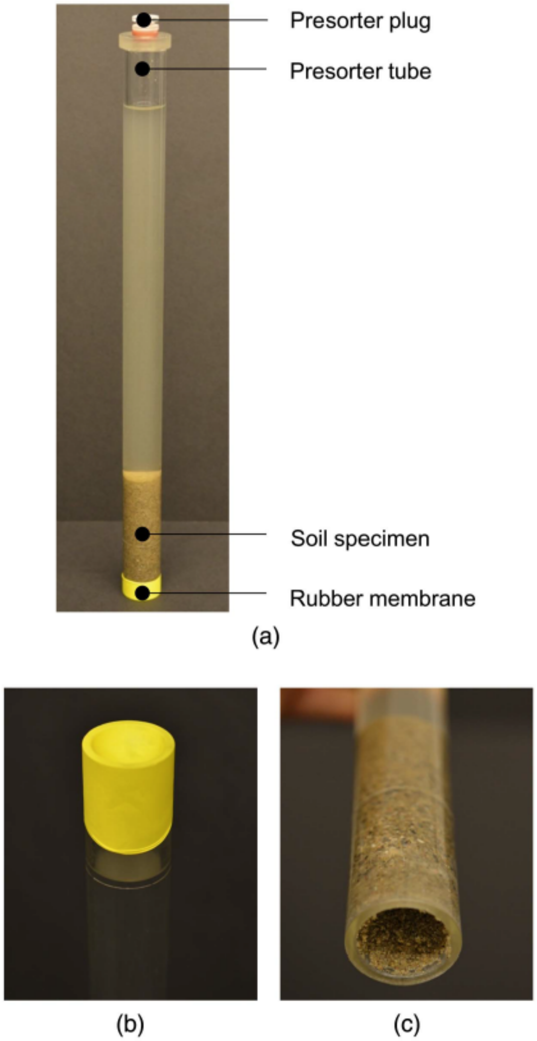

Fig. 5. Presorter: (a) overall system; (b) presorter vacuum-sealed by rubber membrane; and (c) soil held in the tube by vacuum after the membrane is removed.

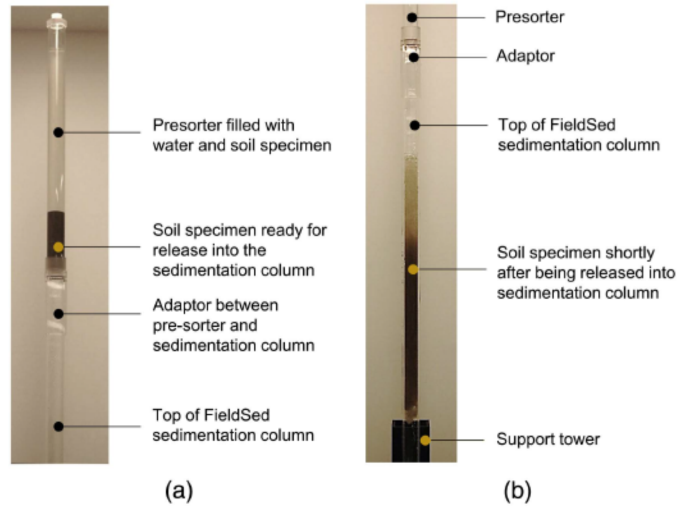

Fig. 6. Soil specimen release from the presorter: (a) prior to release; and (b) several seconds after release.

An 85 ± 15 g soil specimen is funneled into the presorter through the open end, and the tube is filled between 80% and 90% with water. The open end of the tube is sealed with a thin rubber membrane; the membrane is pushed slightly into the tube, thereby creating a vacuum seal [Fig. 5(b)]. The soil and water are vigorously mixed. The presorter is then inverted so that the membrane-sealed end is on the bottom. and the sand is allowed to settle atop the inwardly recessed membrane. Coarse-grained soil particles come to rest atop the membrane in about 10–15 s. The rubber membrane is then slipped off the presorting tube. Because of the vacuum, the soil does not fall out of the opened tube [Fig. 5(c)]. The tube is transferred to the top of the sedimentation column [Fig. 6(a)]. The presorter's rubber plug [Fig. 5(a)] is then removed, which rapidly releases the soil-water mixture into the sedimentation column [Fig. 6(b)]. The particles are sorted by size while settling and, in a matter of minutes, come to rest at the bottom. The specimen is then photographed on all four sides.

Because of its light weight, the FieldSed can be transported and used at remote field locations, on construction sites, and in other nontraditional laboratory settings. Even more beneficial, the low cost of the sedimentation tubes allows many of them to be employed simultaneously for parallel specimen preparation. Thus, the time for soil sedimentation does not cause a bottleneck in a testing program, particularly when many soil specimens are to be tested. This portability and rapid testing throughput are not possible with many of the other available two-dimensional (2D) image analysis methods, particularly those in which noncontacting soil particle assemblies are required (Damadipour et al. 2019; Kumara et al. 2012; Altuhafi et al. 2013; Maiti et al. 2017; Zhang et al. 2012). The FieldSed sedimentation tubes can be set up in a separate rack, as shown in Fig. 7. The soil specimens are released into the columns while in the rack. Once sedimentation is complete, the columns are individually placed into the FieldSed positioning system, quickly photographed, and then returned to the rack or emptied. The concurrent sedimentation of numerous specimens greatly increases the efficiency of SedImaging via the FieldSed.

Specimen Prewashing

Currently, SedImaging by FieldSed works best for coarse-grained soils with particle sizes ranging from 2.0 mm (No. 10 sieve opening) to 0.075 mm (No. 200 sieve opening). A prewashing procedure may be used to determine the percentage of soil mass outside of this range. The prewashing effectively removes particles larger than 2 mm and smaller than 0.075 mm, without specimen-drying, prior to using the FieldSed.

The first step of the prewashing involves a visual inspection of a specimen for particles larger than 2.0 mm. If the specimen does appear to have larger particles, it is washed over a No. 10 sieve. The material retained on the sieve is air- (or hot pan) dried, and the dry weight ($W_{>\text{No. }10}$) is recorded. While the material retained on the No. 10 sieve is drying, the remainder of the specimen is transferred to the presorter. Once the soil is in the presorter, water is added to a marked height. The tube with the specimen and water is weighed (W_{pre}). Next, the presorter is sealed, and the soil-water mixture is vigorously agitated for several seconds. Following agitation, the user sets the tube upright, allowing the coarser particles to begin settling. After around 30–90 s, the tube is unsealed, and the suspended fines-water mixture is carefully poured over a No. 200 sieve. The material passing the No. 200 sieve can be retained for other laboratory testing (e.g., Atterberg limits) if desired.

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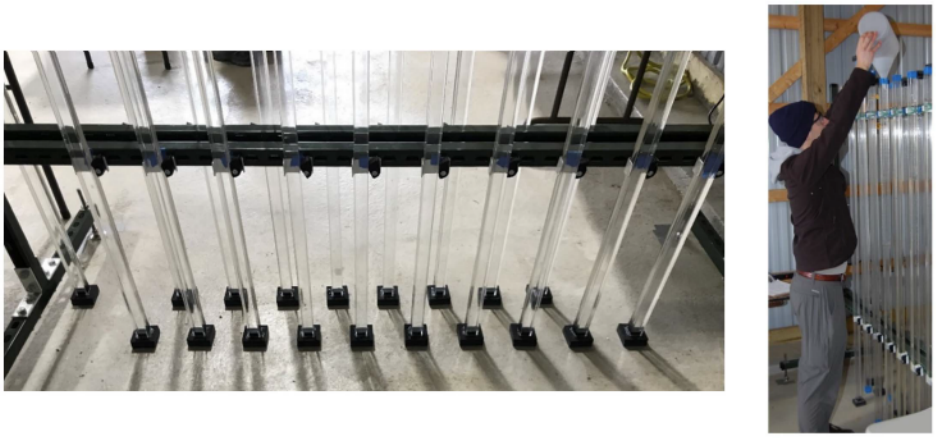

(a) (b)

Fig. 7. FieldSed parallel testing hardware: (a) sedimentation columns in a testing rack (reprinted from Ventola and Hryciw 2019, © ASCE); and (b) a technician preparing many sedimentation columns.

Clean water is added to the presorter, and the agitation process is repeated several times until the water in the tube is observed to be relatively clear after agitation. After the final pour over the No. 200 sieve, any material retained on the sieve is carefully returned to the tube. The presorter is filled with clean water to the marked height, and the weight of the tube and its contents is again recorded (W_{post}). The material that remains in the tube is the weight of the specimen portion having particle sizes between 0.075 and 2.0 mm ($W_{No. 200\text{-}No. 10}$). This material is then released into a FieldSed column and, following sedimentation, is photographed. A HWT-based PSD is generated for this portion of the specimen; the curve is later adjusted to reflect the portions of the original specimen that were retained on the No. 10 sieve ($W_{>No. 10}$) and that passed the No. 200 sieve ($W_{<No. 200}$). The total dry weight of the specimen ($W_{total,dry}$) is

$$W_{total,dry} = W_{>No. 10} + W_{<No. 10} \tag{1}$$

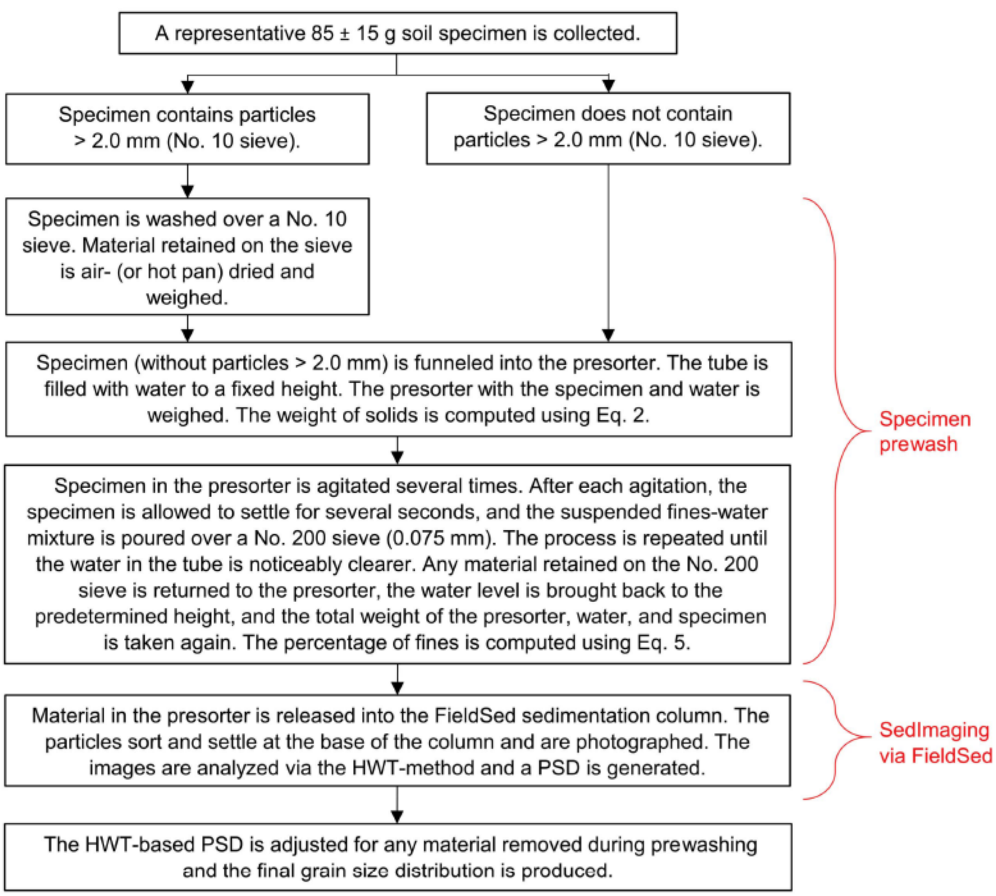

Fig. 8. SedImaging by FieldSed summary diagram.

where

$$W_{<\text{No. 10}} = \frac{G_S \times (W_{\text{pre}} - W_{\text{tube}})}{(G_S - K)} \tag{2}$$

$$W_{\text{No. 200-No. 10}} = \frac{G_S \times (W_{\text{post}} - W_{\text{tube}})}{(G_S - K)} \tag{3}$$

$$W_{<\text{No. 200}} = W_{<\text{No. 10}} - W_{\text{No. 200-No. 10}} \tag{4}$$

where $W_{\text{total,dry}}$ = total dry weight of the soil specimen (g); $W_{>\text{No. 10}}$ = weight of material retained on the No. 10 sieve (g); $W_{<\text{No. 10}}$ = weight of material passing the No. 10 sieve (g); G_S = specific gravity of solids at 20°C; W_{pre} = weight of presorter, water, and soil specimen before agitations (g); W_{tube} = weight of presorter filled just with water (g); K = water temperature correction coefficient [Table 2 in ASTM D854-14 (ASTM 2014b)]; $W_{\text{No. 200-No. 10}}$ = weight of material between the No. 200 and No. 10 sieves (g); W_{post} = weight of presorter, water, and soil specimen after agitations (g); and $W_{<\text{No. 200}}$ = weight of material passing the No. 200 sieve (g).

The fines percentage of the specimen (P_{fines}), which is used for both the Unified Soil Classification System (USCS) and AASHTO soil classifications, is

$$P_{\text{fines}} = \left(\frac{W_{<\text{No. 200}}}{W_{\text{total,dry}}}\right) \times 100 \tag{5}$$

Fig. 8 summarizes the steps in the complete testing procedure for SedImaging by FieldSed that was used for the Kalamazoo River sediment grain size analyses. It includes sample prewashing, SedImaging via the FieldSed, and the final PSD generation using the HWT-based method and prewashing results.

The time needed for prewashing varies from specimen to specimen. Soil specimens with a larger percentage of fines will require more agitation cycles. With some practice, technicians develop a feel for the wait time needed between agitation cycles and the required number of cycles. The procedure is flexible and forgiving;

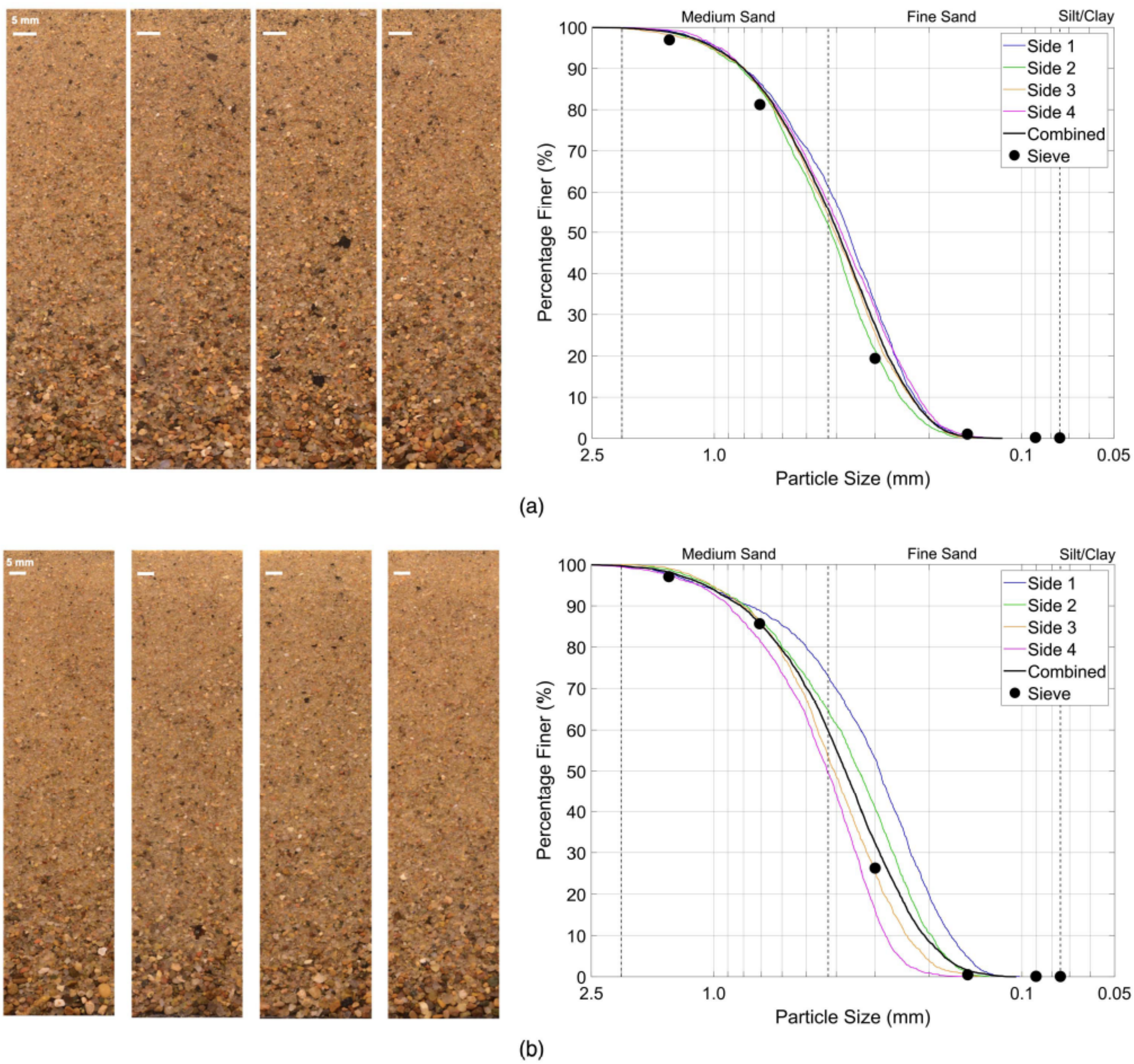

Fig. 9. SedImaging results using the FieldSed: (a) Specimen C; and (b) Specimen D.

if the suspended fines-water mixture is poured too soon, particles larger than 0.075 mm are retained on the No. 200 sieve and simply returned to the presorter. Secondly, not all of the fines must be removed during prewashing. As will be shown in a subsequent example, the HWT-based image analysis (when used on images having sufficient magnification) will detect silt particles. Thus, a specimen's fines percentage found using Eq. (5) could be adjusted if additional fines are detected by the HWT-method. Yet, it is important to note that prewashing is an important practical step in SedImaging. By removing most of the fines, especially clay-sized particles by prewashing, the sedimentation times in the FieldSed columns are greatly reduced.

Field Laboratory and Testing Program

The field laboratory, shown in Fig. 2, was set up by Wood Environment and Infrastructure Solutions, Inc., in a pole barn next to the Kalamazoo River in southwestern Michigan. At the field lab, 118 specimens were selected from sediment cores and analyzed using SedImaging by FieldSed. Without the need for oven-drying, the soil specimens could be tested quickly after their delivery to the field lab. With more time needed to test those that contained larger percentages of fines, the entire testing procedure detailed in Fig. 8 takes between 15 and 35 minutes per specimen. Factors unrelated to the SedImaging test, including work conditions and weather delays, as well as conflicts with technicians' time, resulted in average testing times in the field being longer than those reported previously.

As part of the broad field-testing program of the river sediments, seven samples were taken from separate sediment cores for a quality control investigation. Each sample was homogenized, and an approximately 85 g specimen was tested in the field laboratory. After imaging, the specimen tested in the FieldSed was carefully collected and sent to the Geotechnical Engineering Laboratory at the University of Michigan (UM). There, it was retested using a sister FieldSed system. This was done to evaluate the repeatability of FieldSed results obtained by different technicians under different environmental and lighting conditions. The remaining untested homogenized sample was also sent to UM.

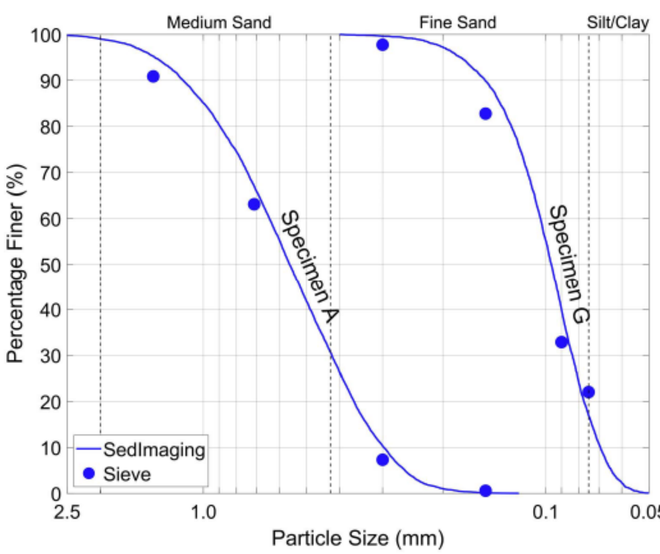

Fig. 10. Specimens A and G PSDs of the material tested in the FieldSed.

Additional SedImaging tests were also performed on specimens taken from previously untested bag materials sent to UM. As with the specimens tested in the field lab, about 85 g of each UM lab sample was tested according to the procedure in Fig. 8: it was prewashed (if necessary) and then tested by FieldSed. This second set of SedImaging tests was performed to evaluate the repeatability of the entire testing procedure, including prewashing. The remainder of the bag material sent to UM was sieved according to ASTM C136/C136M-14 (ASTM 2014a). This was done to evaluate the repeatability of sample splitting and prewashing. Finally, all SedImaging results by FieldSed were compared to sieving for each soil.

Results

Fig. 9 shows images and PSD results for two of the seven quality control specimens photographed using the FieldSed. They do not include any material removed during prewashing. The specimen in

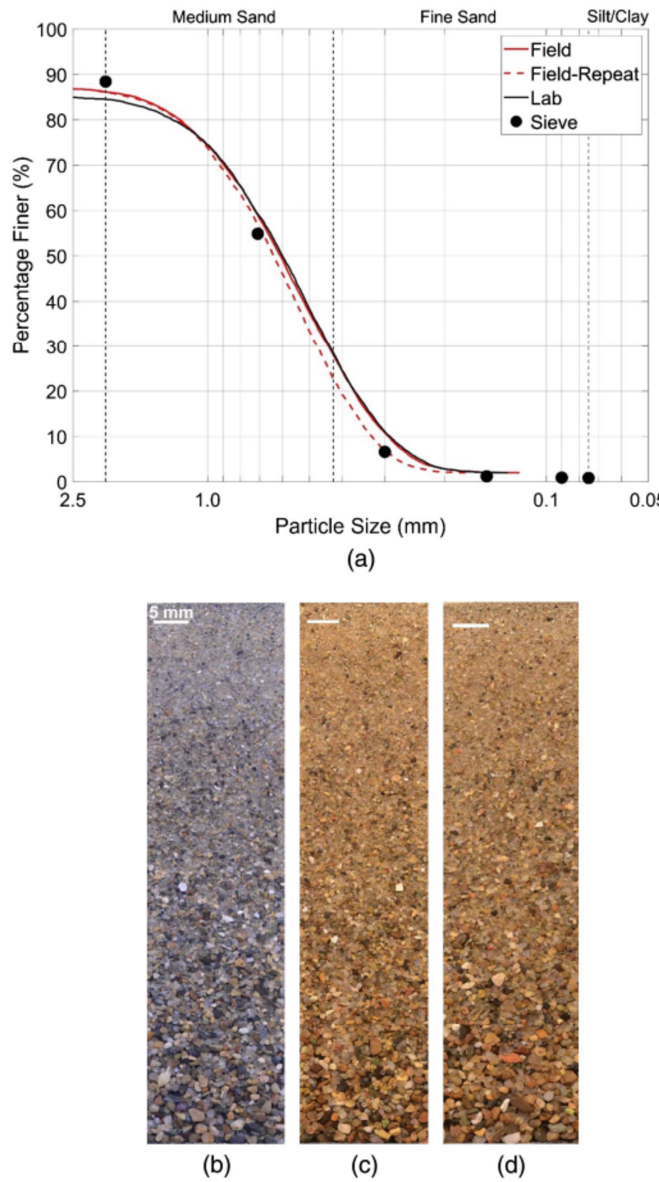

Fig. 11. Specimen A: (a) verification PSDs; (b) field; (c) field-repeat; and (d) lab photographed FieldSed sides.

Fig. 9(a) (referred to as Specimen C in the set of seven quality control tests) is an example in which the HWT-based PSDs of the four photographed sides are nearly identical. However, occasionally, differences are observed between the four images, which warrants the development of a single combined PSD. Fig. 9(b) shows Specimen D that, among the seven control specimens, has the largest difference between its four images. Specimen D's Sides 1 and 2 contain slightly less of the coarsest particles than do Sides 3 and 4. This is reflected in the specimen's four PSDs. The PSDs are all similar in shape but are slightly shifted horizontally from one another, with Sides 1 and 2 reporting smaller percentages of medium sand than Sides 3 and 4.

For both Specimens C and D, the data from all four sides are combined into one total PSD and are plotted as the black lines in Figs. 9(a and b). The specimens were also sieved according to ASTM C136/C136M-14, and the results are shown by the solid circles. For both specimens, excellent agreement between the *combined* PSD and *sieve* is observed. Regardless of the variations between the four images of a specimen photographed in the FieldSed, combining the particle size data into one composite PSD tends to yield an accurate representation of the specimen. Composite PSDs were used throughout the quality control investigation, and when necessary, were adjusted for any material that was removed by prewashing.

Fig. 10 shows the PSDs for the coarsest (A) and the finest (G) of the seven quality control specimens. Like those in Fig. 9, the PSDs in Fig. 10 reflect only the material that was photographed with the FieldSed and excludes any soil that may have been removed by prewashing. These two specimens were also sieved according to ASTM C136/C136M-14, and the results are plotted for comparison to the SedImaging PSDs. The excellent agreements suggest that SedImaging by FieldSed should also provide PSDs comparable to those obtained by sieving for gradations between Specimens A and G.

Figs. 11–17 contain the complete PSDs for the seven control specimens. For each, the PSDs generated from the SedImaging's HWT image analysis method are compared to sieve data. Unlike those in Figs. 9 and 10, the HWT-based PSDs are now adjusted

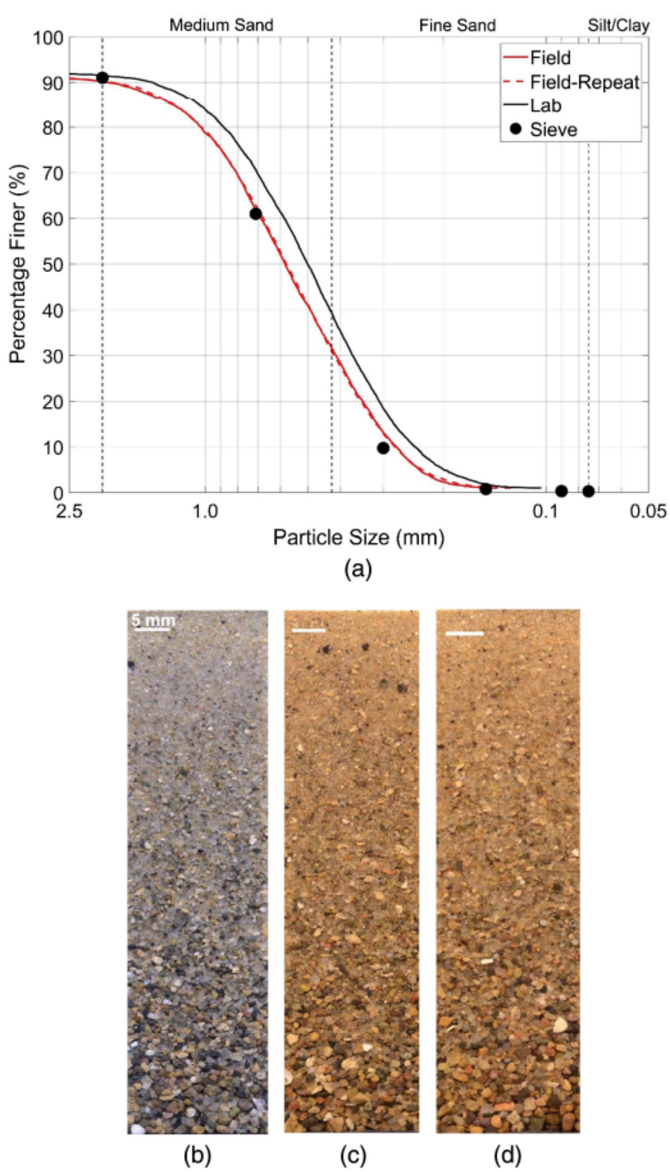

Fig. 12. Specimen B: (a) verification PSDs; (b) field; (c) field-repeat; and (d) lab photographed FieldSed sides.

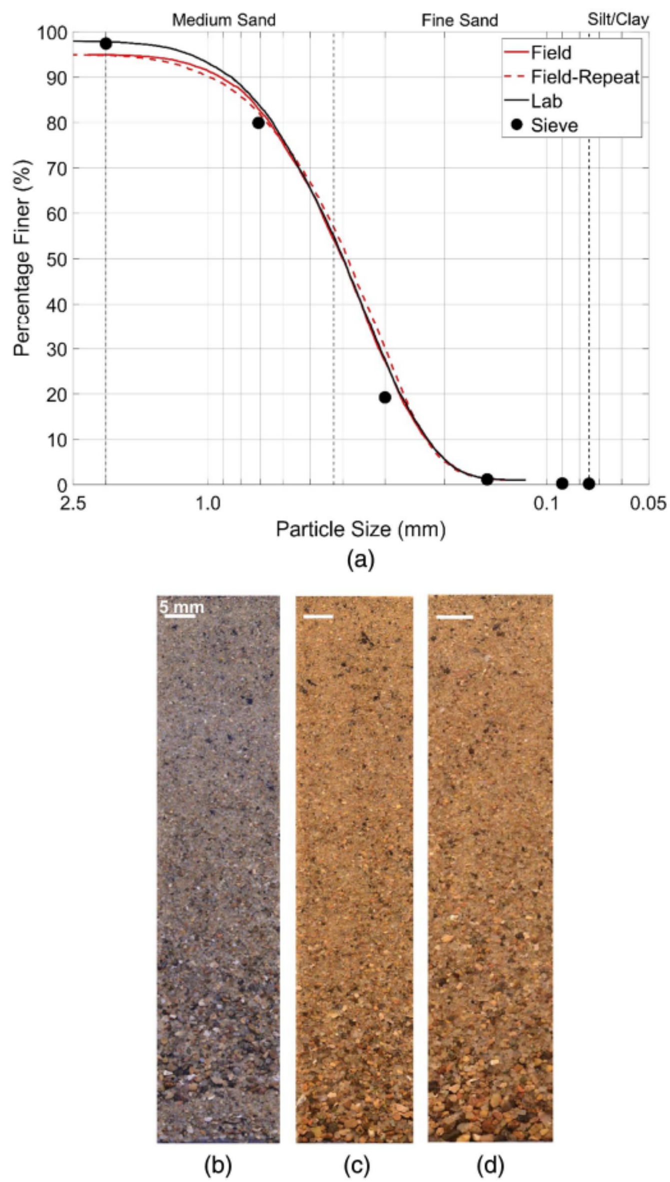

Fig. 13. Specimen C: (a) verification PSDs; (b) field; (c) field-repeat; and (d) lab photographed FieldSed sides.

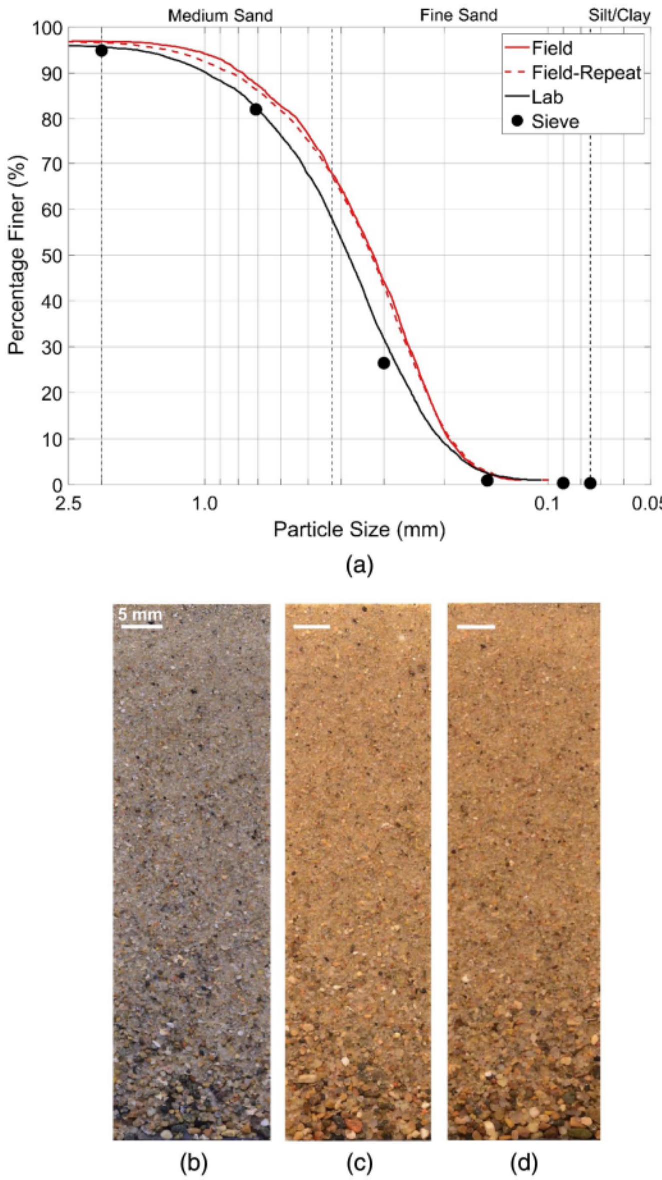

Fig. 14. Specimen D: (a) verification PSDs; (b) field; (c) field-repeat; and (d) lab photographed FieldSed sides.

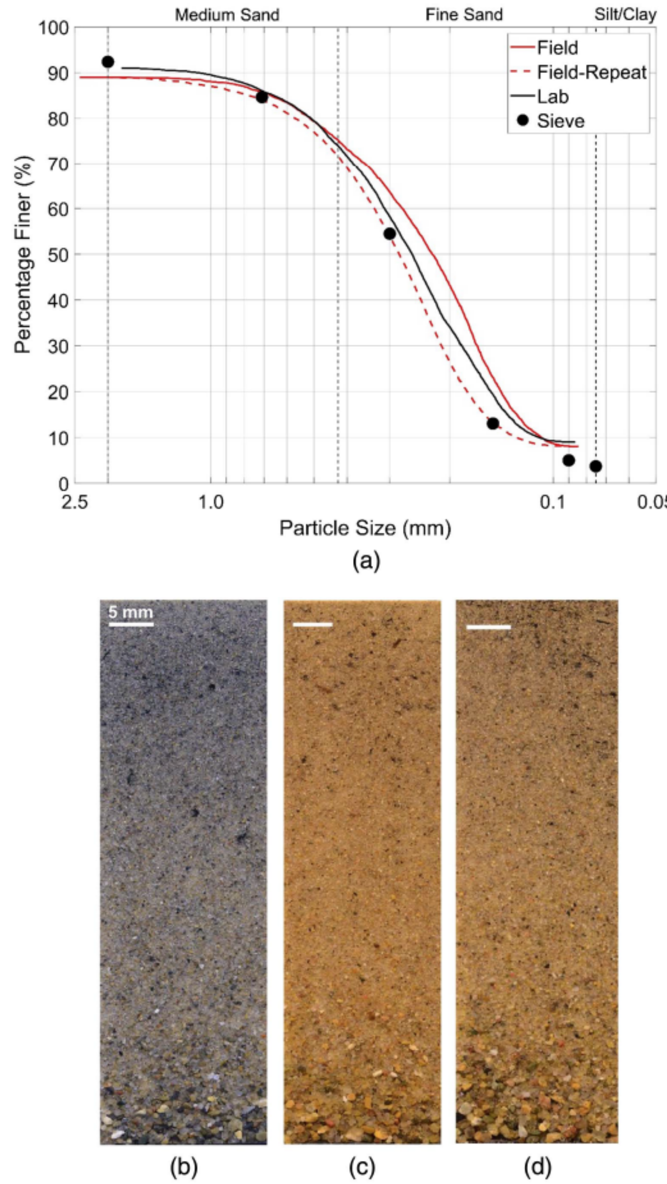

Fig. 15. Specimen E: (a) verification PSDs; (b) field; (c) field-repeat; and (d) lab photographed FieldSed sides.

for the material removed during prewashing. The PSDs of the specimens photographed in the field are referred to as *Field*, while *Field-Repeat* are the PSDs of the same specimens retested in the UM laboratory. The percentage of fines used to create the Field-Repeat PSD curves were taken from the original Field test data because the fines had already been removed during the original field tests and were no longer available. *Lab* refers to the additional specimens taken from bags and tested fully (including prewashing) at UM. *Sieve* is the sieve data of the remaining bag material not tested by SedImaging that was sent to UM. Each figure also includes three images, one of the Field specimen sides, one of the four Field-Repeat sides, and one of the four sides from Lab.

Table 1 summarizes various PSD characteristics, including D_{60}, C_U, and the corresponding USCS group name for each of the quality control tests. The table also includes the specimen percentages that were removed by prewashing (if applicable). Using bar graphs, Fig. 18 compares the percentages of each specimen that fall within four particle size ranges: coarser than 2.0 mm (coarse sand or gravel), 2.0–0.425 mm (medium sand), 0.425–0.075 mm (fine sand), and finer than 0.075 mm (silt/clay).

Analysis of Results

By observation of Figs. 11–17, the agreement between PSD results in Field, Field-Repeat, Lab, and Sieve tests is subjectively assessed to be excellent. Any small variations between the four data sets for each specimen can be attributed to the absence or presence of only a few of the coarsest particles, which will cause parallel offsets over the remainder of the PSD curves. For example, in Fig. 12 (Specimen B), the Lab PSD is the same shape but lies slightly to the right of the Field, Field-Repeat, and Sieve PSDs. The Lab specimen contained slightly fewer particles (with diameters larger than 1.0 mm) than the other specimens. Similar parallel PSD curves are observed for Specimens D (Fig. 14), E (Fig. 15), and F (Fig. 16).

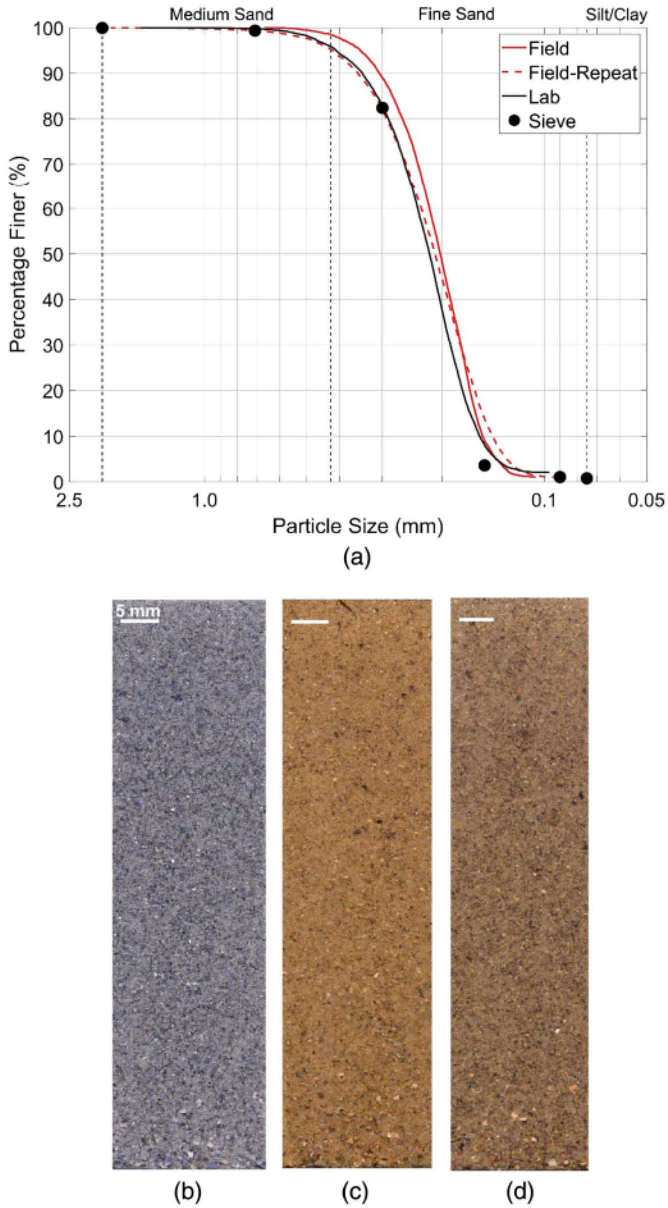

Fig. 16. Specimen F: (a) verification PSDs; (b) field; (c) field-repeat; and (d) lab photographed FieldSed sides.

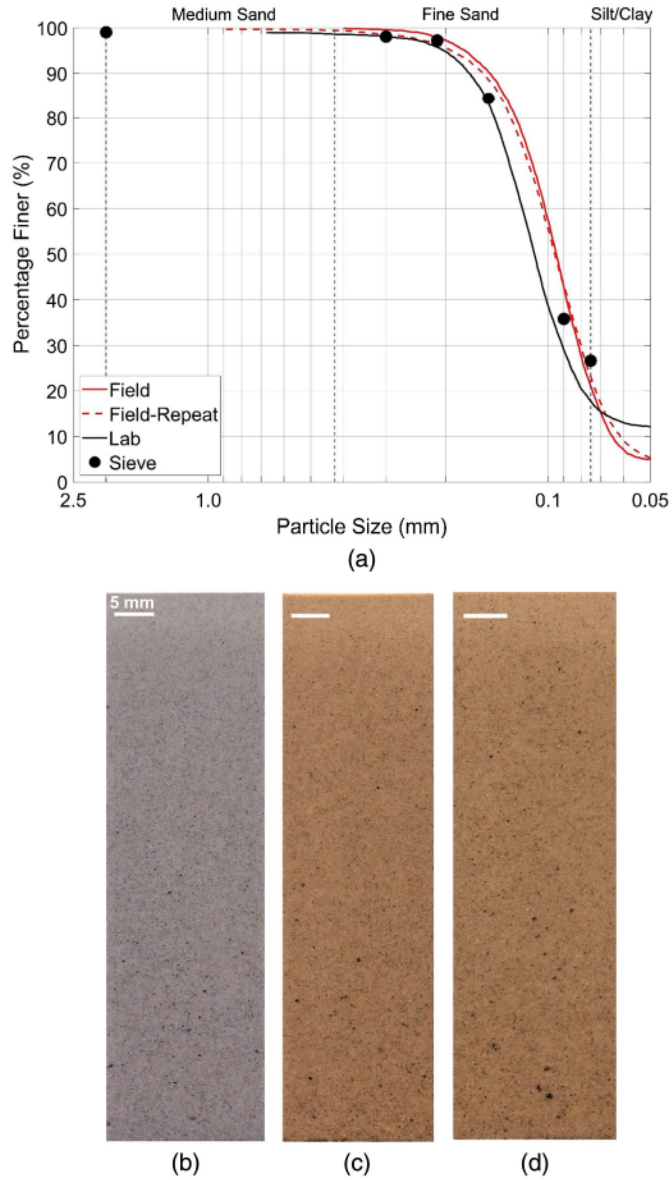

Fig. 17. Specimen G: (a) verification PSDs; (b) field; (c) field-repeat; and (d) lab photographed FieldSed sides.

In addition to the PSDs, it is also useful to compare size distributions by specific ranges (coarse sand or gravel, medium sand, fine sand, and fines), as shown in Fig. 18. For example, in Specimen B, we see nearly identical percentages of the coarsest and finest particles. The only clear difference is that the Lab test suggested 8% more fine (rather than the medium) sand than did the other three tests. This was caused by a slight undersampling of the medium sand for use in the Lab test. The Sieve results agreed perfectly with the Field and Field-Repeat PSDs.

Several general observations can be made by inspection of Figs. 11–17 and Fig. 18. First, a comparison of Field and Field-Repeat data confirm the repeatability of results by SedImaging using FieldSed. This means that the sorting of particles during sedimentation is both effective and repeatable. It also confirms that the particles photographed on the four sides of the column are representative of the material in the interior that is not in the camera view. This is particularly apparent with Specimens A (Fig. 11) and C (Fig. 13) in which there is exceptional agreement among the four sets of PSD data. These seven sets of tests further illustrate the insensitivity of the FieldSed results in environmental changes and, specifically, differences in ambient lighting. As seen in the specimen photos in Figs. 11–17, the Field specimens were photographed in natural light, whereas the Field-Repeat and Lab were photographed with overhead fluorescent lighting. The final PSDs of these three tests were not impacted by the different lighting conditions.

Secondly, the HWT-generated PSDs, once adjusted for material removed by prewashing, show a strong correlation with traditional ASTM sieve results. This confirms the accuracy of the sample splitting procedures used by field technicians and, more importantly, of the prewashing method itself. The figures confirm that prewashing does a very good job of removing the out-of-range sized particles from the specimens prior to FieldSed testing.

Discussion

The results for Specimen G (Fig. 17) are noteworthy, as this material contained more fines than the other specimens. According

Table 1. Verification testing of select Kalamazoo River specimens

Specimen	Test	D_{60} (mm)	D_{50} (mm)	D_{30} (mm)	D_{10} (mm)	C_U	C_C	USCS soil classification[a, b, c]	Retained on #10 sieve (%)[d]	Passing #200 sieve (%)[d]
A	Field	0.72	0.60	0.44	0.29	2.48	0.93	a	13	2
	Field-repeat	0.74	0.63	0.47	0.32	2.31	0.93	a	13	2
	Lab	0.72	0.60	0.44	0.29	2.48	0.93	a	15	2
	Sieve	0.75	0.63	0.47	0.33	2.27	0.89	a	—	—
B	Field	0.68	0.58	0.42	0.28	2.43	0.93	a	9	1
	Field-Repeat	0.68	0.58	0.42	0.28	2.43	0.93	a	9	1
	Lab	0.59	0.50	0.37	0.24	2.46	0.97	a	8	1
	Sieve	0.70	0.59	0.41	0.30	2.33	0.80	a	—	—
C	Field	0.46	0.40	0.31	0.23	2.00	0.91	a	5	1
	Field-repeat	0.45	0.39	0.30	0.23	1.96	0.87	a	5	1
	Lab	0.46	0.40	0.31	0.23	2.00	0.91	a	2	1
	Sieve	0.50	0.43	0.33	0.24	2.08	0.91	a	—	—
D	Field	0.37	0.33	0.25	0.19	1.95	0.89	a	3	1
	Field-repeat	0.37	0.33	0.25	0.19	1.95	0.89	a	3	1
	Lab	0.44	0.38	0.29	0.21	2.10	0.91	a	4	1
	Sieve	0.45	0.40	0.31	0.22	2.05	0.97	a	—	—
E	Field	0.28	0.22	0.16	0.11	2.55	0.83	b	11	8
	Field-repeat	0.33	0.28	0.21	0.14	2.36	0.95	b	11	8
	Lab	0.31	0.26	0.19	0.11	2.82	1.06	b	9	9
	Sieve	0.33	0.28	0.21	0.13	2.54	1.03	a	—	—
F	Field	0.22	0.20	0.18	0.14	1.57	1.05	a	0	1
	Field-repeat	0.23	0.21	0.18	0.15	1.53	0.94	a	0	1
	Lab	0.24	0.22	0.19	0.15	1.60	1.00	a	0	2
	Sieve	0.24	0.22	0.19	0.15	1.60	1.00	a	—	—
G	Field	0.10	0.095	0.080	0.064	1.56	1.00	c	0	5
	Field-repeat	0.10	0.095	0.080	0.060	1.67	1.07	c	0	5
	Lab	0.12	0.11	0.09	—	—	—	c	1	12
	Sieve	0.11	0.10	0.08	—	—	—	c	—	—

[a]SP, poorly graded sand.
[b]SP-SM, poorly graded sand with silt or SP-SC, poorly graded sand with clay.
[c]SM, silty sand, SC, clayey sand, or SM-SC, silty, clayey sand.
[d]Via prewashing.

to Table 1, the field technicians removed only 5% of the fines from their sample by prewashing. By contrast, 12% of the fines were removed in the Lab specimen. In the Field, Field-Repeat, and Lab FieldSed photographs, the HWT-based image analysis reported additional fines in the specimens that were not removed during prewashing. The PSD of Specimen G in Fig. 10 shows an example of this. There, around 17% of the material tested in the FieldSed (after prewashing) was reported as fines. The numbers of fines recorded during prewashing and those that were noted using the HWT-based analysis were combined to yield the specimen's total percentage of fines, as seen in Fig. 17.

Although there was a significant difference in the number of fines removed during prewashing between the field and at UM, when the corresponding HWT-based PSDs were appropriately adjusted, the results were similar. The final HWT-based PSDs more closely match the sieve data. As mentioned previously, this success is attributed to the HWT method being able to detect silt particles that remain in a specimen even after prewashing, assuming that images are taken at sufficient magnification. While it is concluded that the FieldSed image analysis somewhat compensates for incomplete prewashing, more research is needed to test the particle size limits of the FieldSed analysis. This quality control investigation was an early indication that silty sands and possibly sandy silts may be characterized by SedImaging using FieldSed.

The FieldSed and HWT results may also be immune to some abnormalities that may arise during sedimentation. In the Field test of Specimen C (Fig. 13), the soil particles appear to have been deposited in two stages. This was attributed to an inadvertently stepwise release of soil from the presorting tube. As a result, instead of the larger particles continuously grading to smaller particles over the full specimen height, some of the smaller particles are found beneath larger ones, as observed in Fig. 13(b). This was an extremely rare occurrence in the Kalamazoo River FieldSed testing program but is mentioned in this study because it happened to occur in one of the control tests. Despite this unusual abnormality, the final Field HWT-based PSD for Specimen C was in excellent agreement with the other PSDs.

Conclusions

Particle size distributions were rapidly determined for numerous sediment samples taken from the Kalamazoo River using a SedImaging test at a field laboratory. The system for sedimenting and photographing the soil specimens is named FieldSed to distinguish it from its larger predecessor, LabSed. The new system features light-weight, low-cost components that allow many specimens to be prepared and tested concurrently. Seven of the specimens were

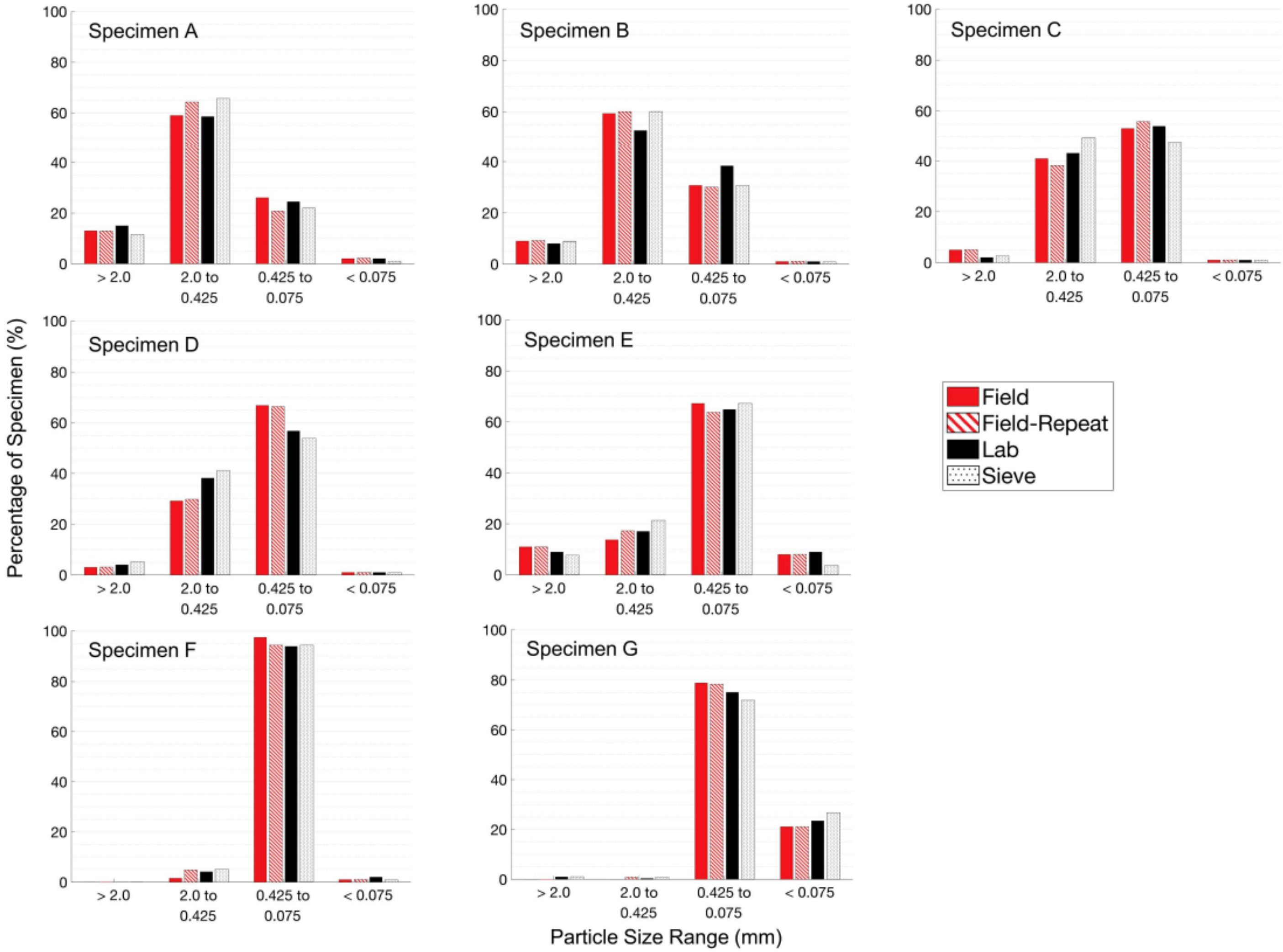

Fig. 18. Particle size distributions by size ranges for quality control for Specimens A through G.

chosen for a control study to evaluate the repeatability of SedImaging by FieldSed and its accuracy based on the agreement with traditional sieving results. The control study has shown that the test is repeatable, and the results are highly comparable to sieving results.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data). These items include the SedImaging code, the field and laboratory data, calculations, and the FieldSed images of the seven specimens presented in this study. Contact the authors for the applicability of a nondisclosure agreement/conflict-of-interest check.

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References

Altuhafi, F., C. O'Sullivan, and I. Cavarretta. 2013. "Analysis of an image-based method to quantify the size and shape of sand particles." *J. Geotech. Geoenviron. Eng.* 139 (8): 1290–1307. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000855.

ASTM. 2014a. *Standard test method for sieve analysis of fine and coarse aggregates*. ASTM C136/C136M-14. West Conshohocken, PA: ASTM.

ASTM. 2014b. *Standard test method for specific gravity of soil solids by water pycnometer*. ASTM D854-14. West Conshohocken, PA: ASTM.

Buscombe, D. 2008. "Estimation of grain-size distributions and associated parameters from digital images of sediment." *Sediment. Geol.* 210 (1): 1–10. https://doi.org/10.1016/j.sedgeo.2008.06.007.

Damadipour, M., M. Nazarpour, and M. T. Alami. 2019. "Evaluation of particle size distribution using and efficient approach based on image processing techniques." *Iran. J. Sci. Tech. Trans. Civ. Eng.* 43 (1): 429–441. https://doi.org/10.1007/s40996-018-0175-3.

Graham, D. J., I. Reid, and S. P. Rice. 2005. "Automated sizing of coarse-grained sediments: Image-processing procedures." *Math. Geol.* 37 (1): 1–28. https://doi.org/10.1007/s11004-005-8745-x.

Guida, G., F. Casini, and G. M. B. Viggiani. 2017. "Contour fractal analysis of grains." *EPJ Web of Conf.: Powders & Grains* 140: 05008. https://doi.org/10.1051/epjconf/201714005008.

Hryciw, R. D., H.-S. Ohm, and J. Zhou. 2015. "Theeoretical basis for optical granulometry by wavelet transformation." *J. Comput. Civ. Eng.* 29 (3): 04014050. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000345.

Kozakiewicz, J. 2018. "Image analysis algorithm for detection and measurement of Martian sand grains." *Earth Sci. Inf.* 11 (2): 257–272. https://doi.org/10.1007/s12145-018-0333-y.

Kumara, J. J., K. Hayano, and K. Ogiwara. 2012. "Image analysis techniques on evaluation of particle size distribution of gravel." *Int. J. Geomate* 3 (1): 290–297. https://doi.org/10.21660/2012.5.1261.

Kuo, C.-Y., and J. D. Frost. 1996. "Uniformity evaluation of cheesiness specimens using digital image analysis." *J. Geotech. Eng.* 122 (5): 390–396. https://doi.org/10.1061/(ASCE)0733-9410(1996)122:5(390).

Maiti, A., D. Chakravarty, K. Biswas, and A. Halder. 2017. "Development of a mass model in estimating weight-wise particle size distribution using digital image processing." *Int. J. Min. Sci. Technol.* 27 (3): 435–443. https://doi.org/10.1016/j.ijmst.2017.03.015.

Masad, E., and J. W. Button. 2000. "Unified imaging approach for measuring aggregate angularity and texture." *Comp.-Aided Civ. Infrastruct. Eng.* 15 (4): 273–280. https://doi.org/10.1111/0885-9507.00191.

Nie, R., H. Wang, K. Yang, and X. Liu. 2015. "Estimation of the grain-size distribution using semisupervised affinity propagation." *J. Hydrol. Eng.* 20 (12): 04015040. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001229.

Ohm, H.-S., and R. D. Hryciw. 2014. "Size distribution of coarse-grained soil by sedimaging." *J. Geotech. Geoenviron. Eng.* 140 (4): 04013053. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001075.

Shin, S., and R. D. Hryciw. 2004. "Wavelet analysis of soil mass images for particle size determination." *J. Comput. Civ. Eng.* 18 (1): 19–27. https://doi.org/10.1061/(ASCE)0887-3801(2004)18:1(19).

Tutumluer, E., C. Rao, and J. Stefanski. 2000. *Video image analysis of aggregates.* Final Project Rep., FHWA-IL-UI-278. Urbana, IL: Univ. of Illinois Urbana-Champagne.

Ventola, A., and R. D. Hryciw. 2019. "On-site particle size distribution by FieldSed." In *Geo-Congress: Engineering Geology, Site Characterization, and Geophysics*, edited by C. Meehan, S. Kumar, M. Pando, and J. Coe, 143–151. Reston, VA: ASCE.

Zhang, Z., J. Yang, L. Ding, and Y. Zhao. 2012. "An improved estimation of coal particle mass using image analysis." *Powder Technol.* 229 (Oct): 178–184. https://doi.org/10.1016/j.powtec.2012.06.027.