Enhanced Soil Characterization through Advances in Imaging Technology

Caractérisation approfondie de sol grâce aux progrès du traitement d'image

Ohm H.S., Hryciw R.D.
University of Michigan, USA

ABSTRACT: The particle size distribution of coarse-grained soils is traditionally determined by sieve tests. However, image-based techniques may soon replace sieving as they are cleaner, faster and less expensive. A major impediment to adoption of images for soil characterization is the wide range of particle sizes in a typical specimen. With current technology particles spanning two orders of magnitude in diameter can be sized from a single image. However, as camera technology advances, the range of sizes that can be analyzed with a single image increases. Two new systems, the Sedimaging (for 2.0 mm to 0.075 mm particles) and the Translucent Segregation Table (TST) (for 75 mm to 2 mm particles) rapidly segregate the particles by size prior to image capture. However, unlike previous image-based methods, these tests do not require that particles be physically detached from one another. The Sedimaging test requires a camera resolution and lens magnification that can achieve at least 3 image pixels per particle diameter (*PPD*) and the TST requires a minimum *PPD* of 9. The minimum *PPD*s must be achieved while capturing entire specimens in the camera's field of view. Extention of the systems to silt sized particles is explored.

RÉSUMÉ : La distribution granulométrique des sols grossiers est traditionnellement déterminée par tamisage. Cependant, des techniques d'analyse d'image pourraient bientôt remplacer le tamisage car elles sont plus propres, plus rapides et moins coûteuses. L'obstacle majeur à l'adoption des technologies d'imagerie pour la caractérisation des sols est la large gamme de tailles de particules dans un échantillon typique. Avec la technologie actuelle, la taille des particules qui peuvent être analysées avec une seule image est de deux ordres de grandeur. Deux nouveaux systèmes, Sedimaging (pour des diamètres de 2,0 mm à 0,075 mm) et la Table de Ségrégation Translucide (TST) (pour des diamètres de 75 mm à 2 mm) peuvent rapidement séparer les particules par taille avant la capture d'images et il n'est plus nécessaire que les particules soient physiquement isolées les unes des autres. Le test Sedimaging nécessite une résolution de la caméra et de l'objectif d'au moins 3 pixels de l'image par diamètre de particules (*PPD*) et le TST nécessite un minimum *PPD* de 9. Le *PPD* minimum doit être atteint tout en capturant un specimen entier dans le champ de vision de la camera. La possibilité d'appliquer ces systèmes aux particules de limon est explorée.

KEYWORDS: Particle size distribution, Soil characterization, Imaging technology

1 INTRODUCTION

The most fundamental characteristic of soils is its particle size distribution. For the coarse soil fraction, the size distribution and subsequent soil classification are determined by sieve analysis. However, sieves and shakers are costly and it takes time to remove jammed soil particles from the sieve openings. The fines fraction must be determined by wet sieving and specimens must be dried and weighed several times. Sieving is also noisy while generating vibrations and air-borne particulates (Ohm et al. 2012). Cleaner and faster image-based methods have emerged as alternatives to sieving. They have the potential added benefit of providing particle shapes and roughnesses.

Several image based particle sizing systems are commercially available. In all such current systems, the particles have to be "detached" from one another prior to photographing. In static techniques, the particles are spread on a flat surface. Two systems that use the static approach are the Aggregate Image Measurement System (AIMS) (Fletcher et al. 2003) and the University of Illinois Aggregate Image Analyzer (UIAIA) (Rao and Tutumluer 2000). Both systems analyze particle sizes and shapes of fine aggregate (sand) and coarse aggregate (gravel). In dynamic techniques, particles drop from a moving conveyor belt into a camera's field of view. A CAMSIZER® (Brown et al. 2005) uses such a conveyor belt system with two cameras at different magnifications. Masad and Tutumluer (2007) provide details of these and other commercial devices.

Taking advantage of recent advances in camera technology and image analysis methods, two new image-based analyzers were developed that do not require physical separation of particles. For sand particles smaller than 2 mm, the system is called *Sedimaging*. For larger sands and gravels, a *Translucent Segregation Table* (TST) is used. The two systems are briefly described in this paper with emphasis on the critical role that high resolution digital cameras have made to their development. The minimum particle sizes that can be analyzed by the two systems using different camera resolutions are compared and extention of Sedimaging into the silt-size range is explored.

2 RECENT ADVANCES IN IMAGING TECHNOLOGY

Since their commercial introduction in the late 1990's *digital single lens reflex* (DSLR) cameras have rapidly increased in resolution as measured by image megapixels (MP). Figure 1 shows the resolution history of two commercial lines, DSLR cameras by Nikon and medium format *digital camera back* (DCB) cameras by Leaf. DSLR cameras reached 36 MP in 2012, while DCB cameras had already achieved 80 MP in 2010. Since DCBs cameras are very expensive, DSLR cameras are currently used in the Sedimaging and TST systems.

Many particulates such as pills, agricultural products and even biological cells are digitally imaged. However, they do not possess a very wide range of sizes and therefore, advances in image resolution is not as critical for their respective industries.

By contrast, silt, sand and gravel particles range from 0.002 mm to 75 mm.

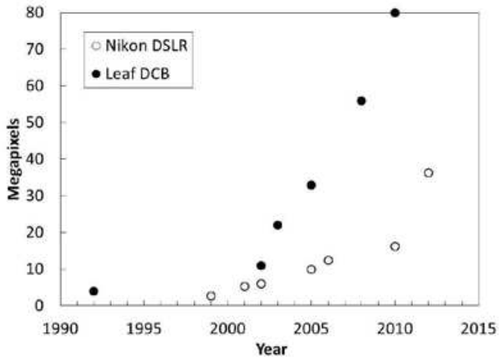

Figure 1. Advances in DSLR and DCB camera resolutions over time.

With pre-2010 lower resolution DSLR cameras, images had to be taken at several magnifications to capture different particle size ranges. Also, multiple images had to be taken at different specimen locations and digitally "stitched" so that a combined image would be a statistically valid representation of the soil. By contrast, using a post-2010 higher resolution camera, a single photo taken at a fixed magnification can produce particle size distributions for soil particles ranging over 2 orders of magnitude in diameter.

3 DIGITAL MEASURE OF PARTICLE SIZE

The size of any object in an image must be determined first in digital pixel units. Conversion to actual dimensions then requires knowledge of the camera & lens system magnification (i.e. image scale). As such, the initial unit of measure for soil particle size is *pixels per particle diameter* (*PPD*) where the diameter corresponds to a square sieve opening as shown in Figure 2. Shin and Hryciw (2004) and Jung (2010) calibrated various image analysis methods against particle sizes as defined by sieving using the *PPD* concept.

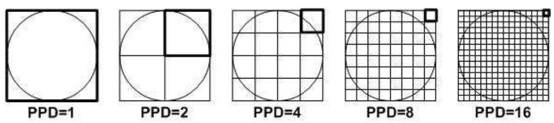

Figure 2. Pixels per Particle Diameter (*PPD*).

4 SEDIMAGING

The Sedimaging (short for sediment imaging) test currently determines the size distribution for 2.0 mm to 0.075 mm soil particles. The apparatus is shown in Figure 3. It consists of a 50 mm × 50 mm × 2000 mm water-filled column through which a soil specimen is sedimented to segregate the particles by size. A sediment accumulator at the bottom of the column contains glass windows though which the soil is photographed following sedimentation. Figure 3 also shows a typical sedimented soil.

A statistical method that correlates particle size via calibration of a mathematical *wavelet index* to *PPD* was developed by Shin and Hryciw (2004). The method requires that the particles in the area of analysis be approximately the same size. Sedimentation facilitates this. Following segregation of the specimen by sedimentation, thousands of overlapping 128 pixel x 128 pixel subareas, contained in ten vertical strips of the image, are analyzed to produce the complete particle size distribution as shown in Figure 4. Details about the test can be found in Hryciw and Ohm (2012).

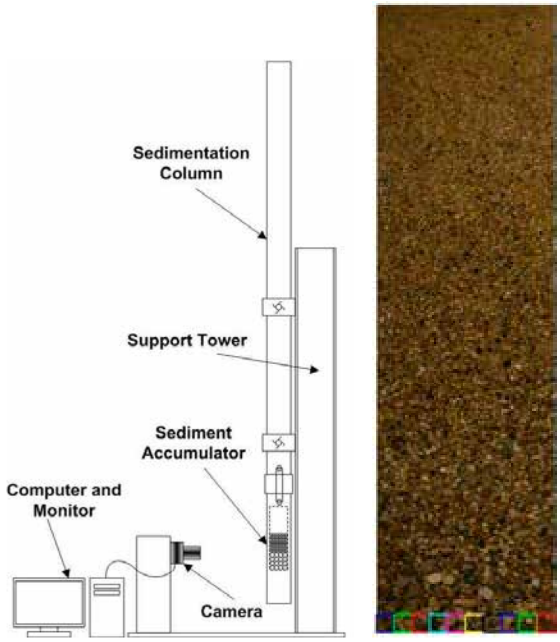

Figure 3. Sedimaging system and typical soil column (Ohm et al. 2012).

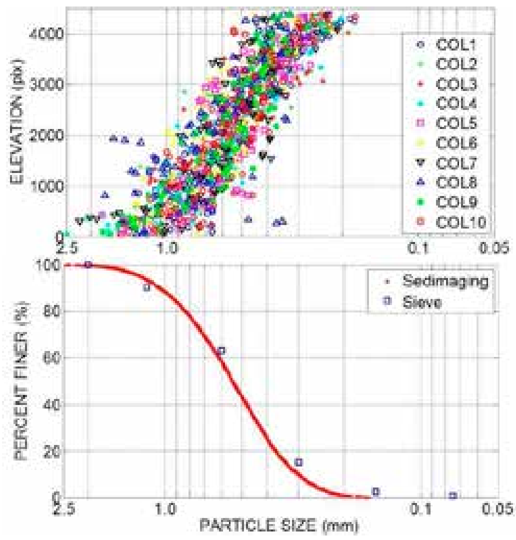

Figure 4. Typical Sedimaging result with comparison to sieving.

Based on Sedimaging tests of sands containing known percentages of silt, the authors found that the minimum *PPD* that can be analyzed by the mathematical wavelet method is 2.7. However, for simplicity this paper will round off and assume a more conservative minimum *PPD* value of 3.0. To explain why so few pixels are apparently needed to size the particles, it is pointed out that the wavelet method does not determine the sizes of every particle individually. It merely analyzes the overall "texture" in each 128 pixel x 128 pixel analysis subarea. As such, it is referred to as a *statistical* method.

5 TRANSLUCENT SEGREGATION TABLE (TST)

A back-lit Translucent Segregation Table (TST) shown in Figure 5 determines size distribution for particles between 75 mm and 2 mm. Whereas a *statistical* image analysis method is used in Sedimaging, the TST utilizes a *deterministic* image analysis approach. A deterministic method counts the actual number of image pixels occupied by each particle. The shape and aspect ratio of each particle can also be determined. For each particle to be individually sized, each must be clearly visible in the image. If small particles are in the vicinity of much larger particles, they can roll and slide beneath the larger particles and be partially or even entirely hidden from view. As such, the TST shown in Figure 5 provides a nominal segregation of particles by size. This is accomplished by temporarily inclining the TST and introducing a soil specimen at the top of the incline. The particles roll and slide down the slope passing beneath a series of bridges of decreasing underpass height, thus segregating the particles by size. While the TST prevents smaller particles from hiding behind larger ones, the particles may still be in contact with one another. After lowering the table and removing the bridges, the TST is photographed from above. The photograph is converted into a binary image and *watershed analysis* (Ghalib and Hryciw 1999) segments the contacting particles. Figure 6 shows a typical TST test result. Additional TST details are provided by Hryciw and Ohm (2012).

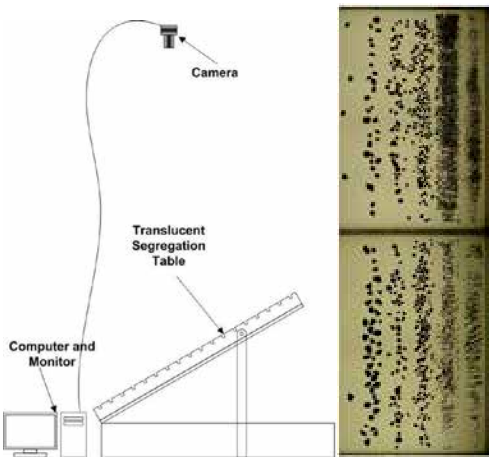

Figure 5. Translucent Segregation Table (TST).

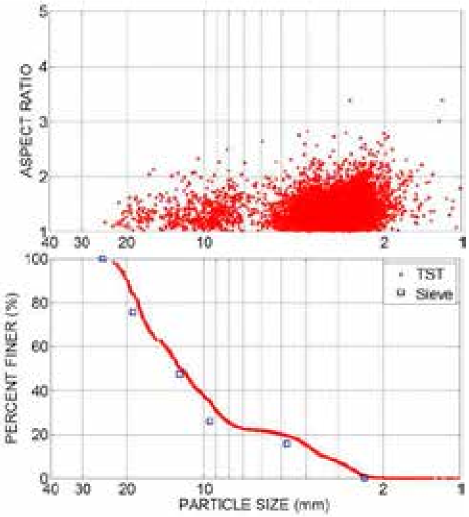

Figure 6. Typical TST result with comparison to sieving.

The minimum *PPD* for the TST test is dictated by the watershed segmentation method and the need to adequately define the particles' projected areas. To find this minimum *PPD*, different quantities of coffee beans were placed on the TST and photographed. The percentage of the image area covered by the coffee beans was varied from 20% to 70% as shown in Figure 7. Different *PPD*s were generated by digital downscaling of the original images. Figure 8 compares the number of segmented particles by watershed analysis at different *PPD*s to the number of actual coffee beans. Conservatively, the minimum *PPD* to detect all of the particles appears to be 9. It is also noted that even with a coverage area of 70% (i.e. very high contact between particles) watershed segmentation successfully identified virtually all of the beans. Note that the minimum *PPD* for the TST is three times larger than the minimum *PPD* for Sedimaging. This is because the TST uses a deterministic method that requires good particle perimeter resolution for watershed analysis while Sedimaging uses a statistical method that does not require such resolution.

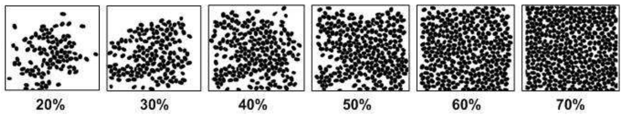

Figure 7. Different image coverage by coffee beans.

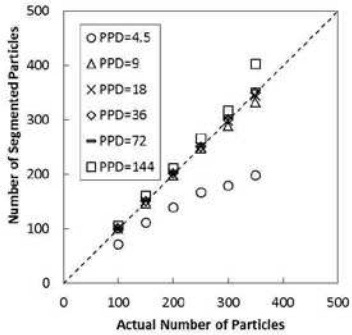

Figure 8. Comparison of segmented versus actual number of coffee beans in the TST for various *PPD*.

6 DISCUSSION

The minimum required *PPD*s for the Sedimaging and TST tests are dictated by their respective image analysis methods. However, this is only one factor that will control the minimum particle size that can be determined in each test with a given camera. The other factor is the area to be photographed. The Sedimaging test requires a specimen weight of 450 g to 500 g. This weight yields a loose sedimented soil column height of no more than 135 mm. For the TST, the longer dimension of the table that must appear in the image is 910 mm. This allows for single- image testing of 1.0 to 1.5 kg specimens. With these requisite parameters and the minimum *PPD* requirements of 3 for Sedimaging and 9 for the TST, the capabilities of four cameras with different resolutions are compared in Table 1. The cameras were selected to represent digital capabilities of the early 2000's (6.1 MP), the presently used Nikon D7000 (16.2 MP) and potential usage of higher resolution Nikon D800 (36.3 MP) and Leaf Credo (80 MP) cameras. While the actual costs of digital cameras decrease regularly, if the current (2012) D100 cost was set at 100 arbitrary currency units, the other three cameras would cost 800, 2500 and 40000 respectively.

The longer Sedimaging and TST image dimensions and the larger of the two pixel resolution directions dictate the required magnification in units of pixels/mm. The required *PPD* then establishes the smallest particle size that can be resolved. Table 1 reveals that the target particle sizes (0.075 mm for Sedimaging and 2.0 mm for the TST) could not be achieved with DSLR cameras in the 2000's. By contrast, currently available cameras are well suited for characterizing particles well into the silt range by Sedimaging and below 1.0 mm by the TST. These calculations suggest that particles in the 2.0 mm to 1.0 mm range could be tested in the TST rather than by Sedimaging. Such a seemingly small decrease in the maximum particle size for Sedimaging would have profound implications to the size and cost of the system. By reducing the maximum particle diameter by 50% the cross section of the sedimentation column could be reduced from $(50\ mm)^2$ to $(25\ mm)^2$. At the same time, the column height could be reduced by more than 50% since settling velocity is proportional to the square of the particle diameter and settling velocity controls particle segregation. The presently large Sedimaging system could become a portable device.

Table 1. Smallest resolved particle sizes by Sedimaging and TST for different camera resolutions.

Camera Model	*Nikon D100*	*Nikon D7000*	*Nikon D800*	*Leaf Credo80*
Year Introduced	2002	2010	2012	2012
Resolution (MP)	6.1	16.2	36.3	80.0
Resolution (pixels × pixels)	3008 ×2000	4928 ×3264	7360 ×4912	10320 ×7752
Sedimaging				
Soil Column Height (mm)	135	135	135	135
Required Magnification (pixels/mm)	22.3	36.5	54.5	76.4
Minimum PPD for Wavelet Analysis (pixels)	3	3	3	3
Smallest Particle Resolved (mm)	0.134	0.082	0.055	0.039
TST				
Longer TST Dimension (mm)	910	910	910	910
Required Magnification (pixels/mm)	3.3	5.4	8.1	11.3
Minimum PPD for Watershed Segmentation (pixels)	9	9	9	9
Smallest Particle Resolved (mm)	2.7	1.7	1.1	0.8

Continuing advances in image sensor technology will yield ever-increasing camera resolutions. This will gradually increase the range of particle sizes that could be analyzed from a single image. At the same time, improvements in optics will gradually increase image magnifications. Common current methods for increasing magnification include macro lenses, diopter rings and extension tubes.

Table 2. Smallest resolved particles by various magnifying systems.

	1)Macro Low Mag.	*Macro High Mag.*	*2)Macro& Diopters*	*3)Macro& Extension*
Magnification (pix/mm)	36.7	209.8	238.1	254.2
Minimum PPD (pixel)	3	3	3	3
Minimum Particle Size (mm)	0.082	0.014	0.013	0.012

1) AF-S Micro Nikkor 60 mm f/2.8G ED
2) Tiffen 62 mm close-up lens +1, +2 and +4
3) Kenko extension tube 12 mm, 20 mm and 36 mm

Table 2 lists the smallest soil particle sizes that could theoretically be detected by wavelet analysis using various combinations of these magnifying systems. A 60 mm macro lens provides magnifications approaching 210 pix/mm. At this magnification the field of view will be too small for Sedimaging but it demonstrates that particles as small as 0.014 mm can be detected. It is also worth noting that a magnification of 1500 pix/mm would be able to detect 0.002 mm particles, the commonly cited silt/clay threshold. Smaller, clay-sized particles would not be detected. The use of diopter rings and extension tubes adds very little to the magnification achieved by the macro lens alone. Furthermore, the authors found that diopter rings and extension tubes decrease the image quality to the point that measures of particle size are noticeably affected. As such, the use of diopter rings and extension tubes is not recommended. Higher magnifications can also be achieved with photomicroscopy at the expense of having a very limited field of view.

7 CONCLUSIONS

Image based systems for determining soil particle size distributions have hitherto required that particles be detached prior to imaging. Two new systems have been developed that eliminate this prerequisite. The Sedimaging system determines size distributions for soils containing particles from 2.0 mm to 0.075 mm while the Translucent Segregation Table (TST) system is used for particles larger than 2.0 mm. Sedimaging uses *mathematical wavelets* to determine particle sizes and requires a camera magnification that provides at least 3 pixels per particle diameter (*PPD=3*). The TST uses *watershed analysis* to digitally detach particles and requires *PPD*=9. Recent DSLR camera advances have provided the requisite camera resolutions and magnifications that have made Sedimaging and the TST practical and cost-competitive with sieving. A much more expensive medium format camera could simultaneously resolve particles spanning nearly two orders of magnitude in diameter, from 2.0 mm to 0.039 mm. Particles as small as 0.014 could be resolved with less expensive DSLR cameras and macro lenses but at the expense of limiting the field of view. With soon available DSLR camera resolutions over 40 MP, the TST system will size particles as small as 1.0 mm. As a result, Sedimaging would be relieved of evaluating particles in the 2.0 mm to 1.0 mm range and thus its physical size could be reduced by 50%.

8 ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. National Science Foundation under Grant No. CMMI 0900105. ConeTec Investigations Ltd. and the ConeTec Education Foundation are acknowledged for their support to the Geotechnical Engineering Laboratories at the University of Michigan..

9 REFERENCES

Brown D.J., Vickers G.T., Collier A.P. and Reynolds G.K. 2005. Measurement of the Size, Shape and Orientation of Convex Bodies. *Chemical Engineering Science* 60, 289-292.

Fletcher T., Chandan C., Masad E. and Sivakumar K. 2003. Aggregate Imaging System for Characterizing the Shape of Fine and Coarse Aggregates. *Transportation Research Record* 1832, 67-77.

Ghalib A.M. and Hryciw R.D. 1999. Soil Particle Size Distribution by Mosaic Imaging and Watershed Analysis. *Journal of Computing in Civil Engineering* 13(2), 80-87.

Hryciw R.D. and Ohm H.S. 2012. Feasibility of Digital Imaging to Characterize Earth Materials. A research report submitted to Michigan Department of Transportation, ORBP Number ORE0908.

Jung Y. 2010. Determination of Soil Grain Size Distribution by Soil Sedimentation and Image Processing. Ph.D. Dissertation, The University of Michigan, Ann Arbor.

Masad E. and Tutumluer E. 2007. Test Methods for Characterizing Aggregate Shape, Texture, and Angularity. NCHRP Report 555, Transportation Reserach Board.

Ohm H.S., Sahadewa A., Hryciw R.D., Zekkos D. and Brant N. 2012. Sustainable Soil Particle Size Characterization through Image Analysis. *Proceedings of the 17th Great Lakes Geotechnical and Geoenvironmental Conference*, Cleveland, Ohio, 26-33.

Rao C. and Tutumluer E. 2000. Determination of Volume of Aggregates. *Transportation Research Record* 1721, 73-80.

Shin S. and Hryciw R.D. 2004. Wavelet Analysis of Soil Mass Images for Particle Size Determination. *Journal of Computing in Civil Engineering* 18(1), 19-27.