FEASIBILITY OF DIGITAL IMAGING TO CHARACTERIZE EARTH MATERIALS

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16. Abstract

This study demonstrated the feasibility of digital imaging to characterize earth materials. Two rapid, relatively low cost image-based methods were developed for determining the grain size distribution of soils and aggregates. The first method, called "sedimaging," provides the grain size distribution for particles between 2.0 mm (U.S. Standard Sieve Number 10) and 0.075 mm (Sieve Number 200) in size. The test utilizes a 7 ft. sedimentation column to rapidly segregate the particles by size. An image processing program based on mathematical wavelet decomposition determines the dominant particle size at approximately 5000 points in an image of the sedimented soil and computes the percentages by size as traditional sieving would. The sedimaging test also reports the percentage of particles smaller than the #200 sieve, the equivalent of "percentage loss by wash" in sieving. The second test utilizes a 3 ft. x 3 ft. tilting backlit Translucent Segregation Table (TST) for obtaining the size distribution of particles in the 40 mm (or larger) to 2.0 mm range. In this test the particles are only somewhat segregated to insure that smaller particles are not hidden from camera view behind larger particles. The dimensions of every particle in the specimen are determined to compute the percentages by size. Results of the Sedimaging and TST tests may be combined to produce a single traditional particle size distribution.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS, ABBREVIATIONS AND SYMBOLS

A	sedimaging test condition parameter
Av	camera aperture size
CA	dimensionless wavelet index
ft.	feet
g	grams
in.	inches
ISO	camera sensitivity
MDOT	Michigan Department of Transportation
mm	millimeters
Mpix	megapixels
NIH	National Institute of Health
No.	number
NSF	National Science Foundation
$P\%F$	Partial Percentage of fines
PPD	pixels per particle diameter
SLR	single lens reflex (camera)
TST	translucent segregation table
T	particle texture index
Tv	camera shutter speed
U.S.	United States
W_a	weight of empty accumulator
W_{a+w}	weight of accumulator filled with water (no soil)
W_c	weight of soil canister
W_s	original dry weight of soil
W_{sa}	weight of soil in accumulator
W_{s+wf+a}	weight of: soil in accumulator + final water in accumulator + empty accumulator
W_{s+c}	weight of dry soil and canister
W_{wf}	final weight of water in accumulator (when soil occupies some volume)
W_{w_o}	original weight of water in accumulator (before soil is introduced)

CONVERSION TABLE FOR U.S. CUSTOMARY AND METRIC UNITS

U.S. Customary		Metric
1 inch (in.)	=	25.4 millimeters (mm)
1 inch (in.)	=	2.54 centimeters (cm)
1 foot (ft.)	=	304.8 millimeters (mm)
1 foot (ft.)	=	30.48 centimeters (cm)
1 ounce (oz.)	=	28.33 grams (g)
1 pound (lb.)	=	0.454 kilograms (kg)
1 fluid ounce (oz.)	=	0.0296 liters (l)
1 fluid ounce (oz.)	=	29.57 milliliters (mL)

Metric		U.S. Customary
1 gram (g)	=	0.0353 ounces (oz.)
1 kilogram (kg)	=	2.205 pounds (lb.)
1 liter (L)	=	33.81 fluid ounces (oz.)
1 milliliter (mL)	=	0.034 fluid ounces (oz.)
1 millimeter (mm)	=	0.0394 inches (in.)
1 millimeter	=	0.0033 feet (ft.)
1 centimeter (cm)	=	0.394 inches (in.)
1 centimeter (cm)	=	0.328 feet (ft.)

EXECUTIVE SUMMARY

A feasibility study of digital imaging to characterize earth materials was performed. Digital imaging was shown to be considerably faster than traditional sieving of soils and aggregates while showing results approximate to that of sieving. Image-based systems are also economically attractive by comparison to other technologies including laser diffraction, x-ray absorption, single particle optical sizing and electrical sensing zone. Finally, image-based techniques can be adapted to a wide range of particle sizes. As such, researchers at the University of Michigan developed two rapid, clean, low-energy, image-based methods for determining the grain size distribution of soils and aggregates. The first method, called Sediment Imaging or "*Sedimaging,"* analyzes the grain size distribution for particles in the 2.0 mm to 0.075 mm range corresponding to openings in Standard U.S. Sieve No. 10 and No. 200 respectively. The second method utilizes a tilting backlit *Translucent Segregation Table (TST)* for obtaining the size distribution of particles in the 40 mm (or larger) to 2.0 mm range. Results from the two tests may be combined to produce a single traditional particle size distribution curve. Both systems utilize a 16.2 megapixel digital SLR camera with a 60 mm macro lens. The cameras are controlled by computer which also performs the image processing and outputs test results to a file or printer.

In the Sedimaging method, the specimen is sedimented through a 2 in. x 2 in. x 7 ft. long water-filled column to segregate the particles by size. The particles come to rest in a few minutes behind a glass window in a detachable sediment accumulator. The resulting 4.5 in. to 5.0 in. column of soil is photographed. An image processing program based on mathematical wavelet decomposition determines the dominant particle size at approximately 5000 points in the image. The particles are ranked by size and converted to volumes to approximate a conventional particle size distribution from sieving. The test does not redefine particle size but rather, through calibrations of the wavelet technique against sieved specimens of soil, simulates the results of sieving. A limited number of comparisons of sedimaging results with sieve tests have shown approximate agreement for a range of soils having different colors, particle shapes and gradations. However, when several tests were performed blind on split samples of one soil, significant differences from sieving results were noted.

In the Translucent Segregation Table (TST) test a dry specimen is introduced at the top of a 3 ft. x 3 ft. tilted translucent back-lit table. The camera is ceiling-mounted about 7.5 ft. above the table. The table contains a series of bridges perpendicular to the slope and of progressively smaller underpass height with distance downslope. The function of bridges is to somewhat segregate the particles by size so that smaller particles cannot hide from view beneath larger ones. After segregation, the table is jolted so that the particles all come to rest on the table and not on top of one another. However, the particles can remain in contact because a "watershed segmentation" image processing method digitally separates them. As with the sedimaging test, only a single image is needed. However, in the TST test the size and dimensions of each particle is determined individually. Both the Sedimaging and TST systems were installed at an MDOT laboratory and personnel were trained in their usage. Based on the statistical analysis performed to date, it was concluded that that the Sedimaging and TST tests could not yet be considered as alternatives to sieving for MDOT acceptance testing.

1. INTRODUCTION

1.1 Introduction and Organization of Report

Under research supported by the Michigan Department of Transportation (MDOT) and additional earlier and current support from the National Science Foundation (NSF), investigators at the University of Michigan have developed two rapid, clean, low-energy, image-based methods for determining the grain size distribution of soils and aggregate. The first method, called Sediment Imaging or "*Sedimaging"*, analyzes the grain size distribution for particles in the range between a U.S. Standard Sieve No. 10 (2.0 mm openings) and U.S. Standard Sieve No. 200 (0.075 mm openings) range. The percentage of fines (particles passing the No. 200 sieve) is also determined by Sedimaging. The second method utilizes a tilting backlit *Translucent Segregation Table* (TST) for obtaining the size distribution of particles larger than the U.S. Standard Sieve No. 10 opening (2.0 mm) and larger. Results from the two tests may be combined to produce a single particle size distribution curve. Both systems utilize a high resolution Nikon D7000 digital single lens reflex (SLR) camera and software developed for interpreting the images and producing the resulting grain size distributions.

The research included a study of existing commercial systems for particle size characterization with an emphasis on system costs, ease of use, testing time and applicability to soils and aggregates in the size ranges commonly used by MDOT.

This research report has been written to also serve as a users' manual for the Sedimaging and TST systems and therefore provides detailed instructions on how to perform the two tests. This first section includes this introduction, the research objectives, scope, methodology and action plan. Next, a technical overview is provided which discusses the unique features of soils and previous shortcomings of available technologies that have hitherto impeded the development of image-based methods for grain size analysis. The sedimaging and TST tests are also introduced in this section.

Sections 2 through 6 provide details on the Sedimaging test while Section 7 through 11 do so for the TST. For both tests, theoretical concepts are presented (Sections 2 & 7) followed by illustrated descriptions of the testing equipment (Sections 3 & 8) and computer programs (Sections 4 & 9). Initial system set-up instructions are given (Sections 5 & 10). Finally, step-by-step testing procedures are provided (Sections 6 & 11) which also serve as the major components of proposed Michigan Test Methods. Section 12 discusses how the results of the two tests are combined into a single grain size distribution when specimens contain particles both smaller and larger than 2.0 mm.

Sections 2 through 12 may be considered as a Sedimaging and TST User's Manual. These sections rely heavily on illustrated color photographs of concepts, system components, computer program interfaces, procedures and typical test results which are included at the ends of each chapter.

The research results are discussed in Section 13 while Section 14 lists the research conclusions. Recommendations for further research and recommendations for implementation are provided in Section 15 and 16 respectively.

Appendices to this report include a bibliography of publications related to processing and interpretation of soil images (Appendix A); a derivation of the equations for computing the percentage of fines (particles smaller than the U.S. Standard Sieve No. 200 opening) in the sedimaging test (Appendix B); example results from sedimaging, TST and combined tests (Appendices C, D and E respectively); sedimaging and TST testing results performed for establishing statistical repeatability (Appendices F and G respectively); and a Review of Commercial Systems for Determination of Soil Particle Size Distributions (Appendix H).

1.2 Objectives

The overriding research objective was to evaluate the feasibility of digital imaging to determine the size distribution of earth materials and, presuming that it is feasible, to develop such a system for soils and aggregates. The five secondary objectives as listed in the original research proposal are itemized below. They are followed by short statements on how the objectives were met. Many additional sub-objectives (e.g. determination of percentage of fines, invention of a new test for particles larger than the U.S. Standard Sieve No. 10 opening (2 mm) arose during the course of the project. These are addressed throughout the report.

1) *To evaluate comparable techniques for grain size determination.*

   A study was completed during the project's first quarter which resulted in an 18 page report attached as Appendix J. The study compared 16 methods (including sedimaging and TST tests) in terms of equipment cost, testing time, ease of usage and suitability to soil and aggregate characterization.

2) *To select the optimum image processing method.*

   Mathematical wavelet analysis calibrated to assemblies of uniform sized soil particles was selected as the optimum method for analyzing images from sedimaging. Other methods including *edge pixel density* and *mathematical morphology* were discarded. For the TST test, image thresholding and watershed segmentation were adopted.

3) To evaluate the effects of particle color and shape on sedimaging results.

Sedimaging

Ten different soils, all but two of which were provided by MDOT were tested to evaluate the effects of particle color and shape on sedimaging results. They ranged in color from black to very light tan while particle shapes ranged from sub-rounded to angular. Whatever effects were caused by soil color could be compensated by illumination of the sedimented specimen. Two calibration curves were used: a standard one for most natural soils and a modified version for mottled particles such as 30A soil.

TST

Some very translucent particles (most commonly quartz) may fall below the imaging threshold and therefore could be uncounted in the TST test. However, for the soils tested, this effect was found to be insignificant. In addition, the shapes of particles are actually determined by the TST test. This is a very attractive feature of the test because mechanical soil and aggregate properties and behavior are known to be highly dependent on particle shape. Sieving yields no information regarding particle shapes.

4) To extend sedimaging to characterization of aggregate.

It was certain from the outset of the research that sedimaging could not handle particles larger than the Standard U.S. Sieve No. 4 opening (4.75 mm). Since MDOT indicated a need to evaluate particles even larger than ¾ in., a completely new test was developed, -the TST. Having two systems, sedimaging would size the minus No. 10 sieve opening fraction of while the TS would size the plus No. 10 sieve opening fraction.

5) To develop a step-by-step Michigan Test Method for aggregate evaluation.

Chapters 6 and 11 of this report are essentially the proposed Michigan Test Methods for the sedimaging and TST tests respectively.

1.3 Scope

The original scope of the research included:

1) Evaluation of commercial systems for soil size determination;
2) Modification of the sedimaging test hardware to include coarse aggregate;
3) Selection of the optimum image processing method;
4) Development of sedimaging software;
5) Evaluation of the effects of soil particle shape and color on sedimaging test results (12 soil types were to be tested);
6) Delivery of one sedimaging system to an MDOT laboratory
7) Training of MDOT personnel on the sedimaging system.

With the realization that a fundamentally different test would need to be developed for the plus sieve No. 10 opening (2 mm) sized aggregate, the scope of the study almost doubled since items 2 through 7 above were distinctly different for the TST and would have to be performed in parallel with the tasks for sedimaging.

Towards the end of the project period, 20 Sedimaging tests and 20 TST tests were added to the scope of the study. These tests were performed to provide a statistical comparison to 40 parallel sieve tests conducted by MDOT. Half of the test specimens were split from the sedimaging and TST specimens, and the other half were blended by weighing out identical amounts of each sieve size. The results of the blind tests performed by the University of Michigan and comparison of results to the parallel sieve tests performed by MDOT are included in Appendix F (Sedimaging) and Appendix G (TST).

1.4 Methodology

The research was conducted by a team of faculty, students and technicians at the University of Michigan. The research methodology is discussed in the framework of the individual responsibilities of the team members. The specific tasks and responsibilities were assigned to each as follows

Roman D. Hryciw (Principal Investigator) oversaw all aspects of the literature review, redesign and construction of the sedimaging and TST hardware; performance and interpretation of tests; presided over twice-weekly meetings with the research team to review progress, update designs, discussed findings and assigned new tasks for the periods between meetings; directed software development; placed all purchase orders; interacted with Project Manager; sought and received information from Al

Robords of the MDOT Aggregate Quality Control Group of the Materials Section at MDOT; oversaw all budget aspects and reviewed financial statements; wrote monthly and quarterly progress reports and co-authored the final report.

Dimitrios Zekkos (Project Co-PI). Professor Zekkos was involved with the quality control and quality assurance of the project. He reviewed the monthly and quarterly reports, participated in group meetings and assisted in the conceptualization of the testing systems. He critiqued the work and assured that the test methods were understandable and that the results are comparable to results obtained by sieving.

Hyon-Sohk Ohm (Graduate Student - PhD Candidate). Performed literature review; assisted with design and prepared all shop drawings of the modified sedimaging and TST systems; prepared soil specimens and performed all sedimaging and TST tests; presented and interpreted results; coded all software for sedimaging and co-authored the final report; participated in all semi-weekly meetings.

Yongsub Jung (post-doctoral student). Co-supervised initial work of Hyon-Sohk Ohm, participated in semi-weekly group meetings; provided design recommendations; worked on software and sedimaging manual; worked on journal paper on sedimaging; contributed significantly to the literature review; worked on alternate image processing methods, including edge pixel density and mathematical morphology; assisted Hyon-Sohk Ohm with evaluation of image processing methods; provided recommendations on high resolution cameras; conceptualized and co-designed pre-segregation system for sedimaging.

Robert Fischer (Senior Machinist - Technician). Advised research team on design of modified sedimaging and TST hardware; ordered parts and supplies; performed all machining of the new systems; participated in quarterly progress meetings with MDOT.

Merick Burch (Senior Technician). Performed all machining of sedimaging pre-segregator and non-metal parts of TST system; advised research team on lighting and support systems for the TST.

Nick Brant (MS graduate student). Took a 3-credit Independent Study with PI during the 1st Quarter during which he collected materials for the literature review; wrote draft of report and subsequent modifications; participated in all semi-weekly group meetings and design discussions during the 1st Quarter.

1.5 Action Plan

The estimated manpower requirements to execute each project task and the project timeline as originally proposed are shown as in 1.1. Although all tasks were completed within the 12 month project period, some logical modifications to the hours and timeline were made during the course of the project as follows:

Table 1.1: Original estimated manpower requirements and anticipated timeline.

Task	Estimated Person Hours	Timeline (Months)
1. Review of literature and comparison of methods	100	1 through 3
2. Performance of Sedimaging tests	500	2 through 8
3. Modification and construction of Sedimaging hardware for aggregate evaluation	400	3 through 7
4. Preparation of step-by-step Michigan Test Method (MTM) for aggregate evaluation.	250	6 through 8
5. Delivery and installation at MDOT	20	8 and 9
6. MDOT Training	20	8 and 9

1. *Review of literature and comparison of methods.* – completed in months 1 through 3.
2. *Performance of sedimaging tests.* – pilot Sedimaging tests were performed on an older system in months 2 and 3 which provided direction for the redesign and construction of a new sedimaging system. Testing on the new system began in month 7 and continued through month 12. The Translucent Segregation Table (TST) system was placed into operation in month 8 and also continued through month 12.
3. *Modification and construction of Sedimaging hardware for aggregate evaluation.* - Redesign of the sedimaging system occurred in months 2 through 4 and construction was completed in month 7 as anticipated. Design of the new TST also began in month 2 and continued through month 11. Final addition of safety features occurred as late as month 12. The authoring of software was added to this task. It continued through month 12 as new features were added.
4. *Preparation of step-by-step Michigan Test Method (MTM) for aggregate evaluation.* - The Michigan Test Methods, essentially Chapters 6 and 11 of this report, were developed in months 8 through 10. The logical delay was dictated by the redesign requirements and addition of new test features such as determination of percentage of fines.

5. *Delivery and installation at MDOT* – Both systems were delivered and installed at the MDOT Metro laboratory in Sterling Heights, Michigan in month 12. This is a deviation from an earlier plan which was to have aggregate suppliers visit the University of Michigan for demonstrations and to conduct extensive testing of soils and aggregates at the university laboratory for statistical analysis of results and comparison to results by sieving.
6. *MDOT training* – Training essentially began in month 7 during a visit to the University of Michigan by Richard Endres, the MDOT the Project Manager; Michael Townley, Transportation Research Program Section Manager; Al Robords, Aggregate Quality Control; Dave Gauthier, Research Advisory Panel; Bill Redmond and Lou Taylor. It continued in Month 11 with visits by representatives of aggregate suppliers Stoneco; Great Lakes Aggregates and Edw. C. Levy Co. Training occurred following installation of the systems at the MDOT Metro Lab in Sterling Heights in month 12 and continued beyond the project time frame at no additional cost to MDOT.

1.6 Technical Overview

1.6.1 Soil Preparation for Image Capture

In-situ soils are generally heterogeneous three-dimensional assemblies of particles having various sizes & shapes and being composed of different minerals. Images taken of soils in their in-situ (mixed) conditions are virtually impossible to analyze for grain size distribution because the captured images are rarely representative of the actual distribution of particle sizes. Smaller particles either block the larger ones from fully appearing in the image or they themselves hide behind the larger particles. Furthermore, single images obtained by currently available high end commercial digital cameras can resolve only 2 to 3 orders of magnitude of particle size. This falls short of the wide range of particle sizes of many, if not most, soils.

As with traditional sieving, a soil specimen must be prepared in a manner which would facilitate an accurate determination of its particle size distribution by imaging. In general, the greater the preparation effort the less demand is placed on image acquisition, processing and interpretation. For example, in the idealized hypothetical case, if all of a specimen's particles could be spread out on a shadow-less (backlit) white or black surface in such a way that no particles are touching each other and we employ an "ideal" digital camera with infinite pixel resolution, perfect focus and positioning far from the specimen so that the field of view is large and edge distortions are insignificant, the grain size distribution could be obtained through simple counting of the image pixels associated with each soil grain. Of course, even if such technology existed, preparation of the specimen so that no particles are touching is impossible since a typical soil specimen contains millions, if not billions of particles. But even for gravels, where the particle count could be merely in the thousands, a complete separation of the particles is, for all practical purposes, unattainable. The challenge was therefore to develop preparation methods that would be "just good enough" so as to allow for accurate determination of grain size distribution using reasonably priced cameras and the image processing and interpretation methods developed specifically for the task. The accuracy of the tests must be judged by comparison to sieving results.

1.6.2 The Sedimaging Test Overview

In the mid-2000's Shin and Hryciw (2004) developed an image processing technique that could determine the average particle size in an image of a 3-dimensional assembly of soil grains provided that the particles were approximately the same size. The image interpretation method is based on mathematical wavelet transforms as will be discussed in Section 2. The soil preparation involves segregating the particles by size by sedimenting the specimen through a 7 ft. long water-filled column. The resulting 3-dimensional assembly at the bottom of the column is then photographed.

Sections 2 through 6 of this report provide complete details of the sedimaging system and test procedures. In the present section, Figures 1.1 through 1.9 illustrate only the main features of the test for interested readers who may not actually be performing the tests themselves. However, even advanced system users are encouraged to begin reading here.

Figure 1.1: The sedimaging system for sizing particles in the 2.0 mm to 0.075 mm range consists of 3 major hardware components. They includes a 7 ft. long sedimentation column with 2 in. x 2 in. inside dimensions; a 22 in. long sediment accumulator with glass windows which attaches to the bottom of the sedimentation column; and an 18 in. pre-segregation tube which acts as both a particle pre-segregator and a release system to introduce the specimen into the water-filled column.

Figure 1.2: Approximately 450 grams of a soil specimen is poured into the pre-segregator which is initially about half-full with water. Additional water is added to fill the tube to about 90% capacity. A rubber balloon is stretched over the open end of the pre-segregator. After stretching, the membrane is pushed into the tube slightly while allowing air to escape. This creates a slight vacuum in the tube.

Figure 1.3: The pre-segregation tube containing the soil & water mixture is shaken until the particles are well mixed then turned vertically with the rubber membrane on the bottom. The coarse-grained fraction of the soil is allowed to settle to the bottom of

the tube. This non-essential step takes less than a minute. With the tube held vertically, the rubber membrane can be rolled off the end of the tube. The vacuum keeps the particles from flowing out.

Figure 1.4: The pre-segregation tube is lowered onto a circular-to-square adaptor on top of the sedimentation column. The adaptor is also shown in Figure 1.1(c). With the pre-segregator in place on the top of the column, the vacuum is released by opening a small vent at the top of the pre-segregation tube (blue plastic cork in Figure 1.1(c)). The loss of vacuum results in an instantaneous release of the saturated specimen into the water-filled sedimentation column below. About 5 seconds later, the largest (2 mm) particles arrive at the bottom at the sediment accumulator.

Figure 1.5: Sedimentation continues for 5 to 10 minutes until all coarse-grained material has settled down in the sediment accumulator. The percentage of particles smaller than 0.075 mm can be determined by draining the water with suspended fines from the sedimentation column through a valve and drainage line located just above the sediment accumulator (seen in Figures 1.4, 1.6 and 1.7). Drainage of the column water takes approximately 3 minutes. For accurate measurement of the percentage of fines, it is advisable to allow at least 3 mm (height) of particles smaller than 0.074 mm to settle in the accumulator, the rest may be drained off.

Figure 1.6: Sedimentation through the long column results in a well segregated column of about 4.5 in. to 5.0 in.) height in the 2 in. x 2 in. sediment accumulator. A 16.2 megapixel (Mpix) Nikon D7000 photographs the sedimented column.

Figure 1.7: The camera is permanently mounted on a camera support column so that it captures the entire sedimented soil column in "portrait" orientation (4928 pixels from top to bottom) with a single photograph. The camera and 60 mm macro lens are pre-set to collect images at a scale of 37 to 38 pixels per millimeter. A small lamp attached to the camera support column illuminates the sedimented column. The image capture is controlled remotely from a computer using software "NKRemote" by Breeze Systems.

Figure 1.8: A computer program, "sedimaging.exe" analyzes a relatively small 128 pix. x 128 pix. region of an image and yields a dimensionless index (*CA*) based on *wavelet mathematics*. As previously discussed, the reason for segregating the specimen by particle size is that the method works best if the particles in the 128 pix. x 128 pix. region are approximately the same size. A calibration curve, based on many soils photographed at many magnifications, relates *CA* to the number of *Pixels per Particle Diameter* (*PPD*). The *CA* yields the *PPD.* Dividing the *PPD* by the image scale

produces the average grain size in millimeters for each 128 pix. x 128 pix. region. Since the calibration is based on particle size as defined by standard U.S. standard sieves, the method does not redefine particle size but rather, gives the size that would have been determined by sieving.

Figure 1.9: The sedimaging.exe program analyzes about 5,000 128 pix. x 128 pix. regions of the segregated column, each generating a single average grain diameter (*PPD*) for the region. The *PPD*s values are taken to the third power to convert them to volume units (note: there is no need to assume a particular 3D particle shape) then sorted to produce a conventional grain size distribution curve for the entire sedimented soil column. The computer program output also includes a photo of the soil column. If desired, the image can be expanded on a computer monitor for close-up inspection of the grains. The permanent visual electronic record may eliminate the need for sample storage after testing.

Figure 1.10: Sedimaging results have shown approximate agreement with sieving results provided that an appropriate representative calibration curve is used. Future features will include an image-based particle shape distribution to accompany the particle size distribution.

1.6.3 The Translucent Segregation Table (TST) Test Overview

To accommodate particles larger than 2.0 mm, the sedimaging system physical dimensions would have to be enlarged to the point of being impractical. As such, a different test is used for gravel-sized materials. A 3 ft. x 3 ft. tilting translucent back-lit table was designed to segregate the particles so that smaller and larger particles would be kept apart. “Smaller and “larger” are relative terms. A “smaller” particle can be thought of as a particle that could roll or slide under a “larger” particle and therefore be hidden from camera view. The specimen is prepared by tilting the table to allow the particles to slide and roll beneath a series of bridges of decreasing underpass height down the incline. The result is that the particles become somewhat segregated by size and spread out on the flat translucent surface. However, contact between the particles is acceptable. Ghalib et al. (1999) introduced a method called *watershed segmentation* to digitally “segment” (i.e. separate) contacting soil particles. The watershed segmentation is part of a public domain image processing program called “ImageJ” developed at the National Institute of Health (NIH). ImageJ is used to interpret the images taken of particles on the translucent segregation table. Unlike the sedimaging test, since the particles are spread out in a single layer on the translucent table, every particle in the specimen is visible and counted. The image interpretation results are converted into a traditional grain size distribution.

Sections 7 through 11 of this report provide details of the TST system and test procedures. As with the Sedimaging figures discussed above, Figures 1.11 through 1.19 illustrate only the main features of the TST test for interested readers who would not be performing the tests themselves. However, advanced users should also begin reading here.

Figure 1.11: The Translucent Segregation Table (TST) is used for sizing aggregate larger than 2.0 mm in size. The specimen is introduced at the top of a tilted translucent back-lit table. The table contains a series of bridges of progressively smaller underpass height with distance downslope. The particles are "swept" down the incline passing beneath the bridges. A particle larger than an underpass is restrained from further downslope motion. A selection of bridge sizes is available and they can be installed at various positions along the inclined plane. The bridge set can be chosen to accommodate an expected particle gradation so that similar volumes of particles held behind each bridge.

Figure 1.12: After sweeping, the inclined table is lowered to its horizontal position and the bridges are removed. This allows an unobstructed view of the particles that are now segregated by size. Perfect segregation is unnecessary because the goal of the segregation is only to minimize the potential for relatively small particles to hide behind larger particles. The particles may remain in contact. However, a mild jolt or shake to the table insures that particles will not be left sitting on top of one another.

Figure 1.13: The segregated particles are photographed by a Nikon D7000 camera permanently mounted above the TST.

Figure 1.14: The image is automatically *thresholded* at a gray-scale level such that the background becomes white and the pixels representing particles become black.

Figure 1.15: *Watershed segmentation* is used to find the boundaries of particles in the thresholded image, even in clusters of contacting particles. The watershed method eliminates the need to separate particles prior to photographing. This reduces the testing time and allows for a larger, more representative specimen to be tested.

Figure 1.16: The TST results show approximate agreement with sieving. Several methods can be used for determining an equivalent particle diameter and for computing particle volumes. These methods and the reasons for small discrepancies with sieving results are discussed in Section 7.

Sedimaging

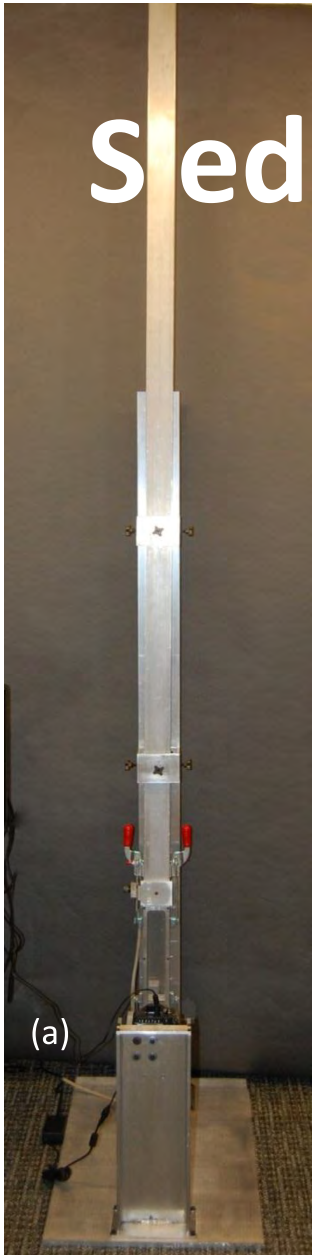


Fig. 1.1 The three main components of the sedimaging system:

(a) sedimentation column
(b) sediment accumulator
(c) pre-segregator.

Fig. 1.2 Placing the specimen in the soil pre-segregation and attaching the rubber membrane.

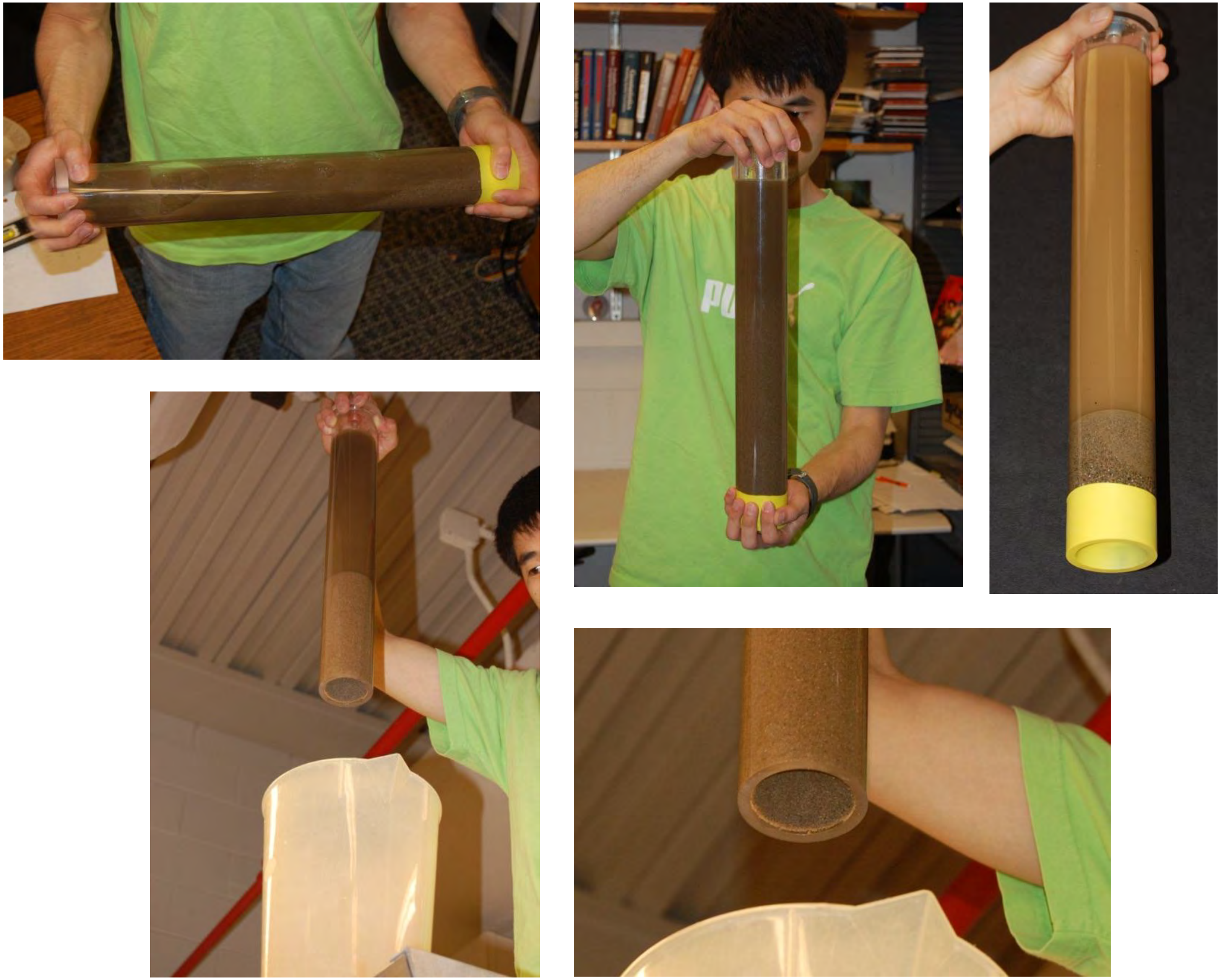


Fig. 1.3 Stirring the soil and water and removal of the rubber membrane.

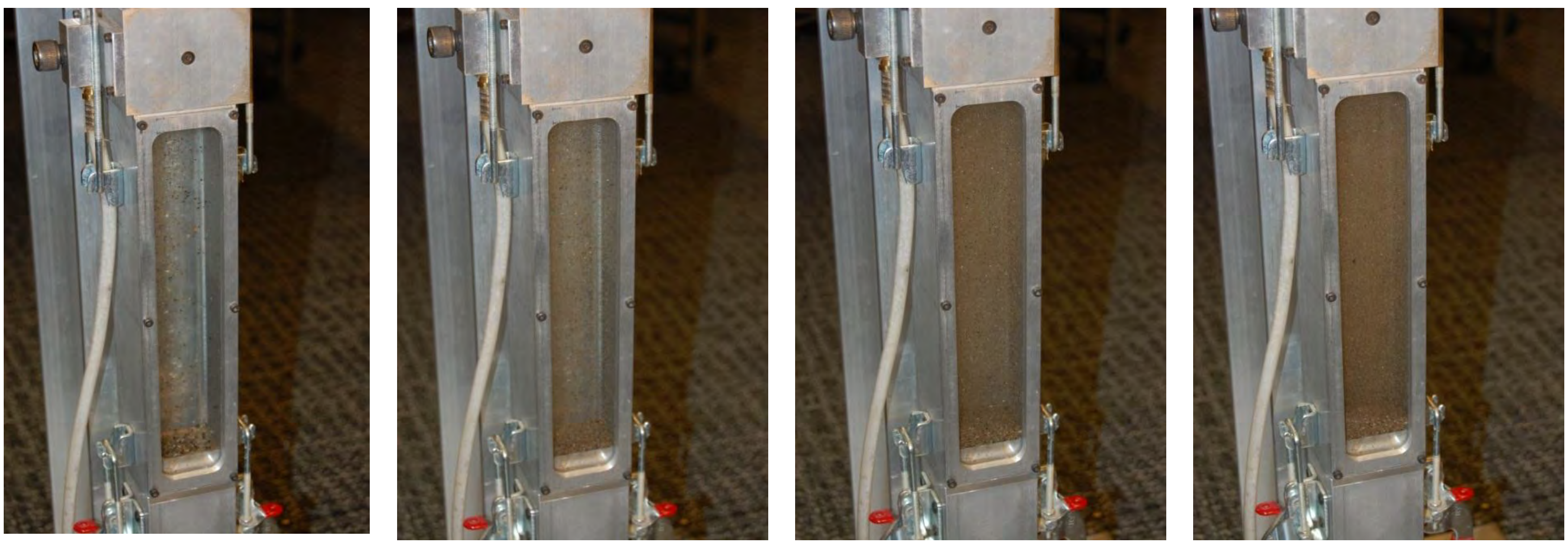


Fig. 1.4 Releasing the specimen into the sedimentation column (top) and first arrivals of the largest particles in the accumulator (bottom).

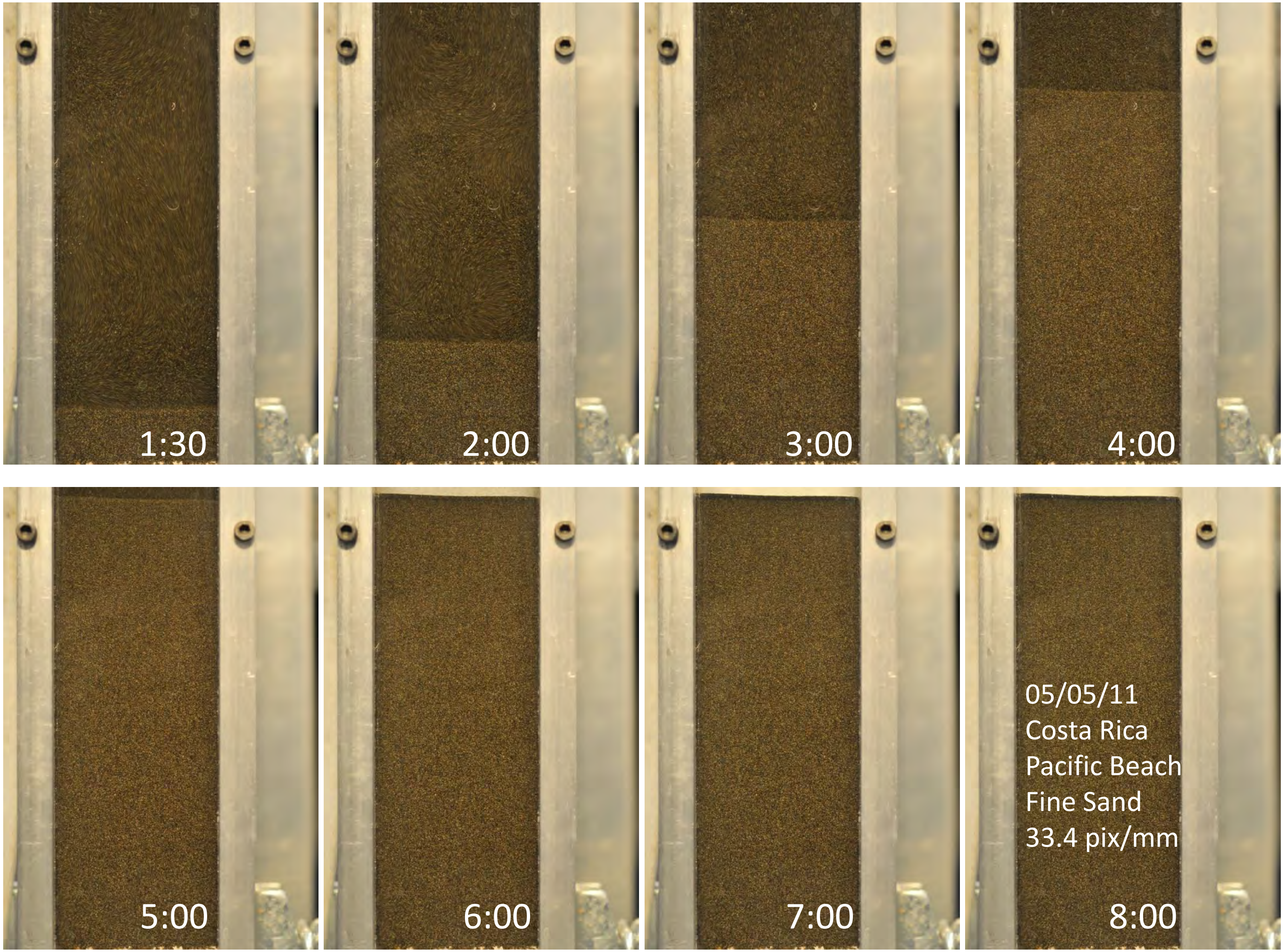


Fig. 1.5 Sedimentation with time.

Nikon D7000
16.2 Megapixels (4928 x 3264)

Fig. 1.6 The fully sedimented soil ready for photographing by a Nikon D7000.

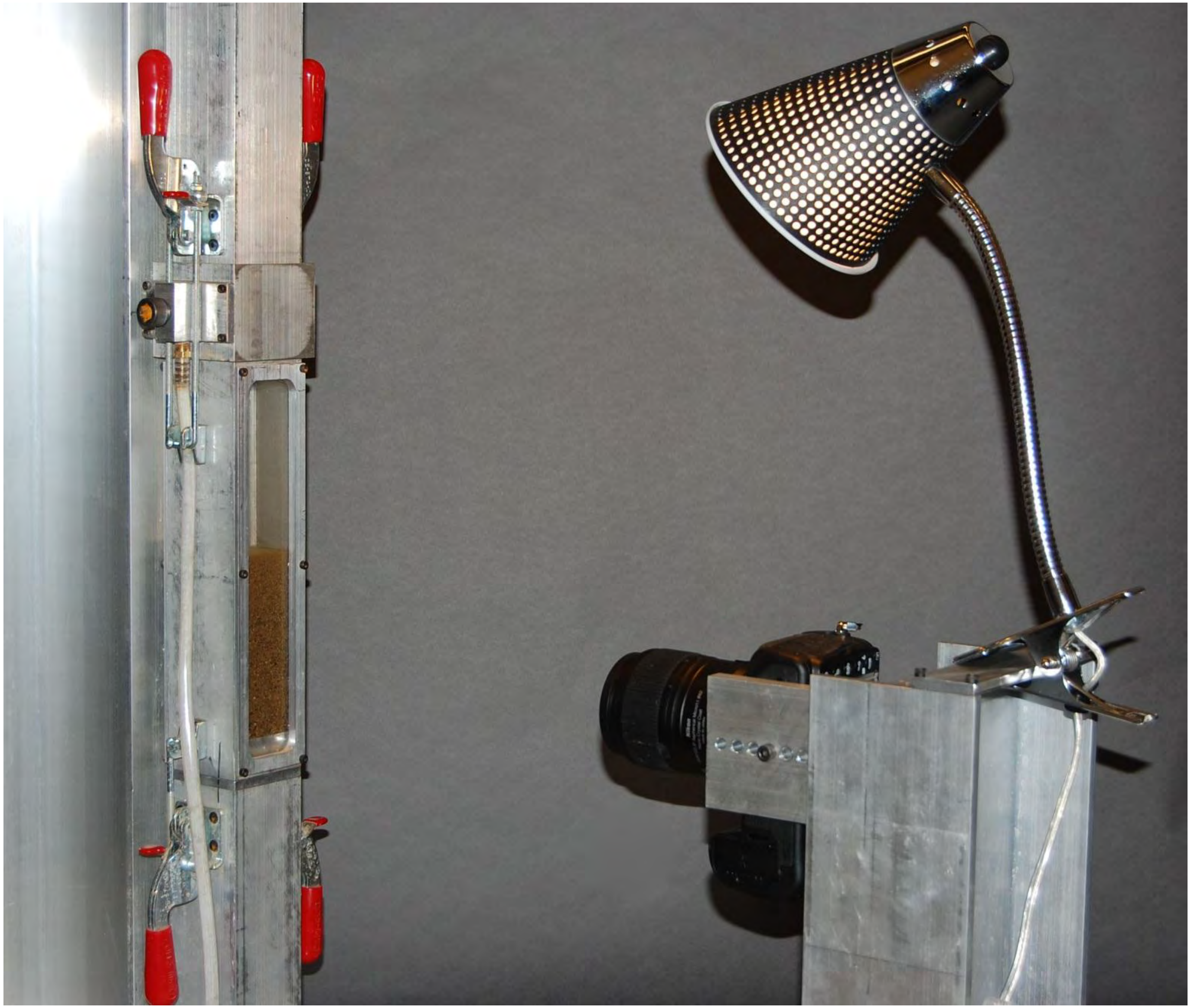


Fig. 1.7 Camera and lighting systems in position.

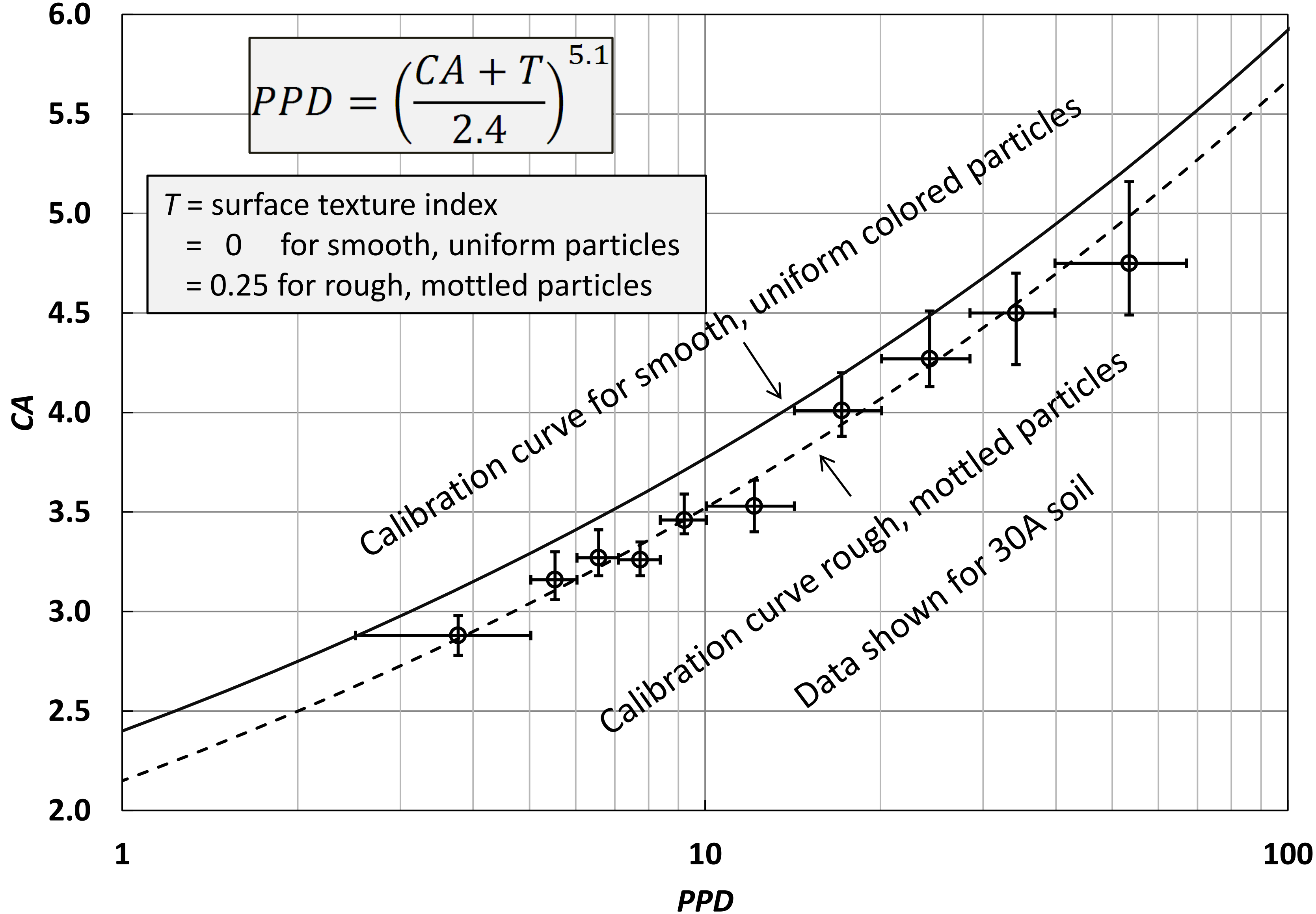


Fig. 1.8 Calibration curve for determining grain size in sedimaging (details in Chapter 2).

Soil: 2NS

Sample Number:

Depth (ft):

Test Date: 04/27/11

Performed by: HS

D_{60} (mm): 0.46

D_{30} (mm): 0.31

D_{10} (mm): 0.21

C_u: 2.16

C_g: 0.99

Avg (mm): 0.28

Mag (pix/mm): 35.0

Image Size (pix): 4040 x 1280

Image Size (mm): 115.4 x 36.6

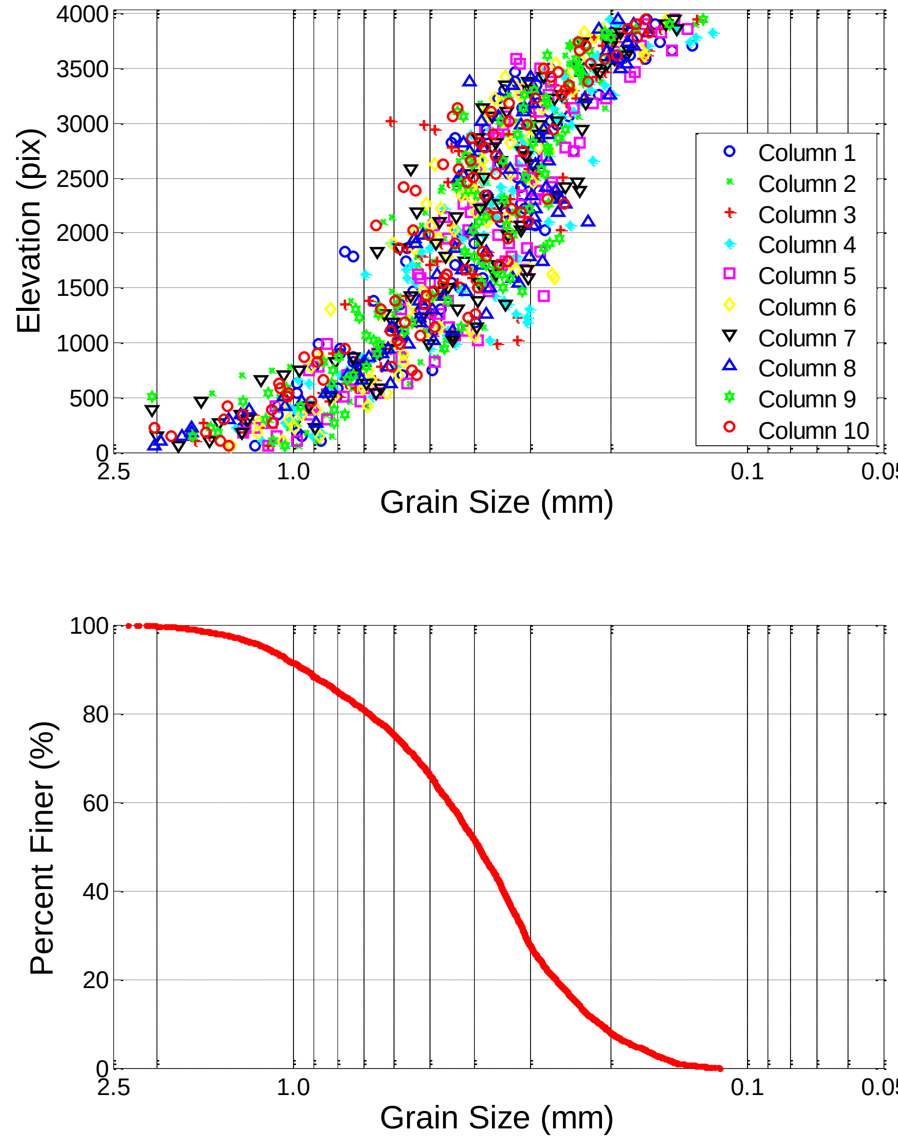


Fig. 1.9 Typical sedimaging program outputs.

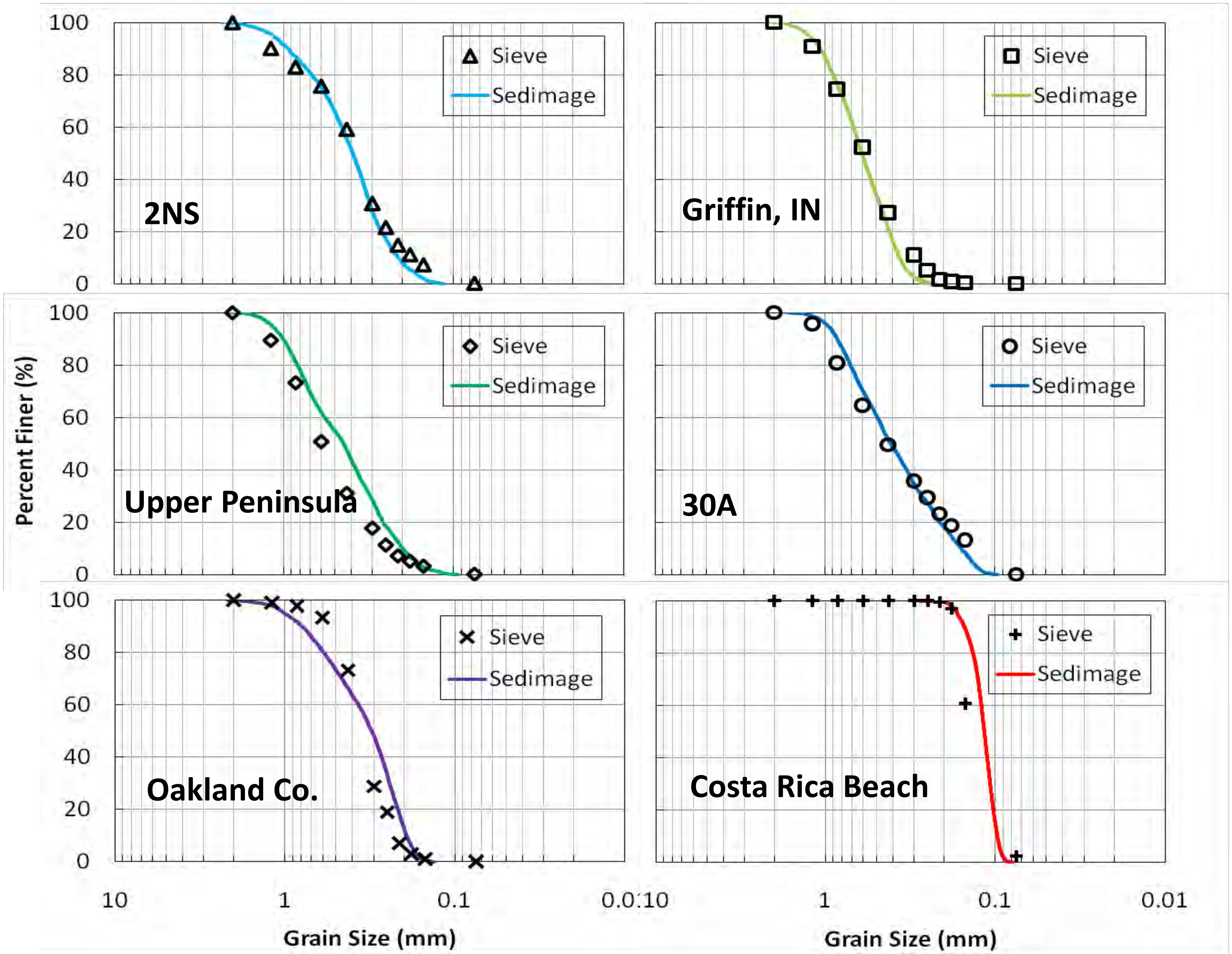


Fig. 1.10 Comparison of sedimaging and sieving results.

Fig. 1.11 The Translucent Segregation Table (TST).

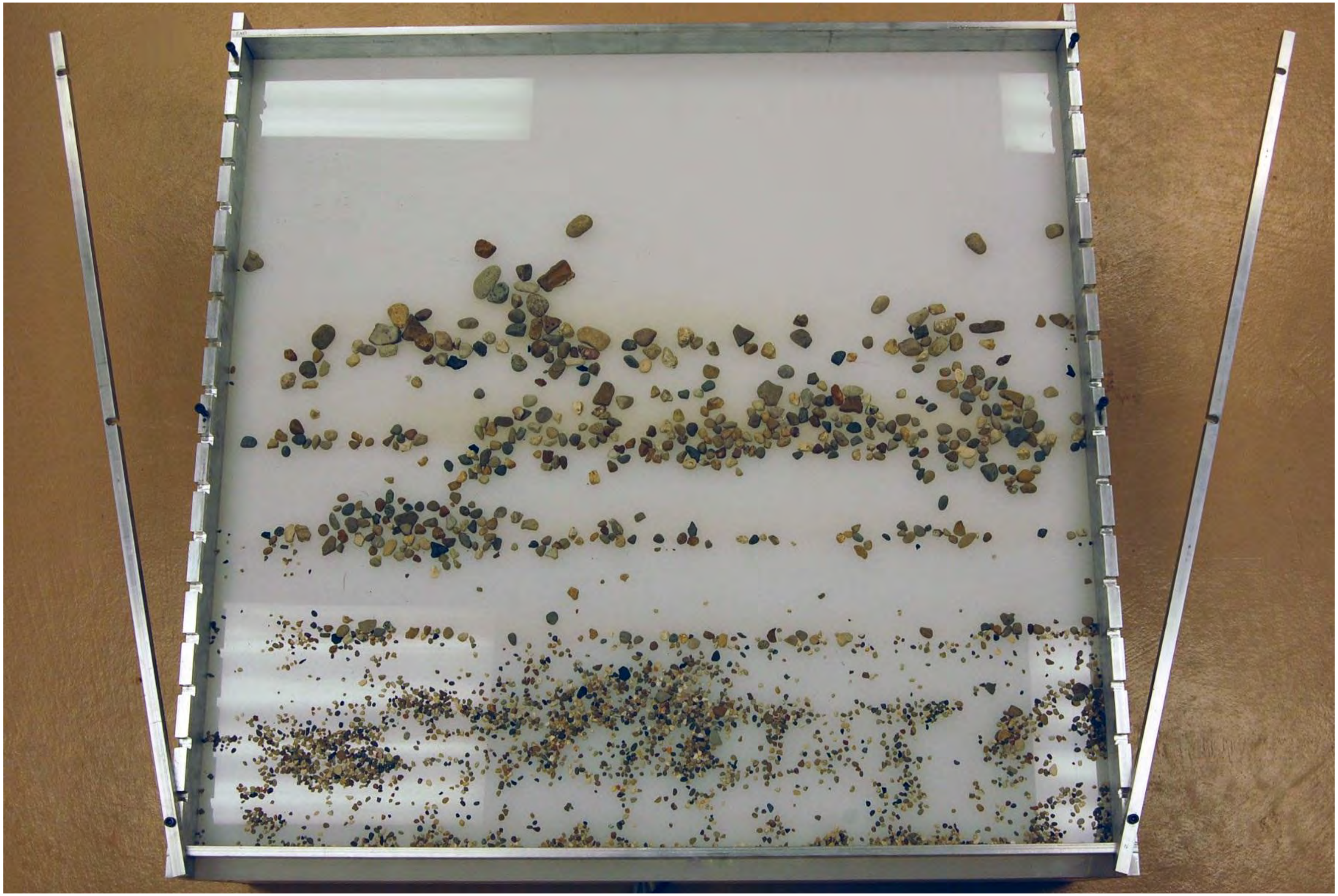


Fig. 1.12 The TST after sweeping and bridge removal.

Fig. 1.13 The segregated particles photographed.

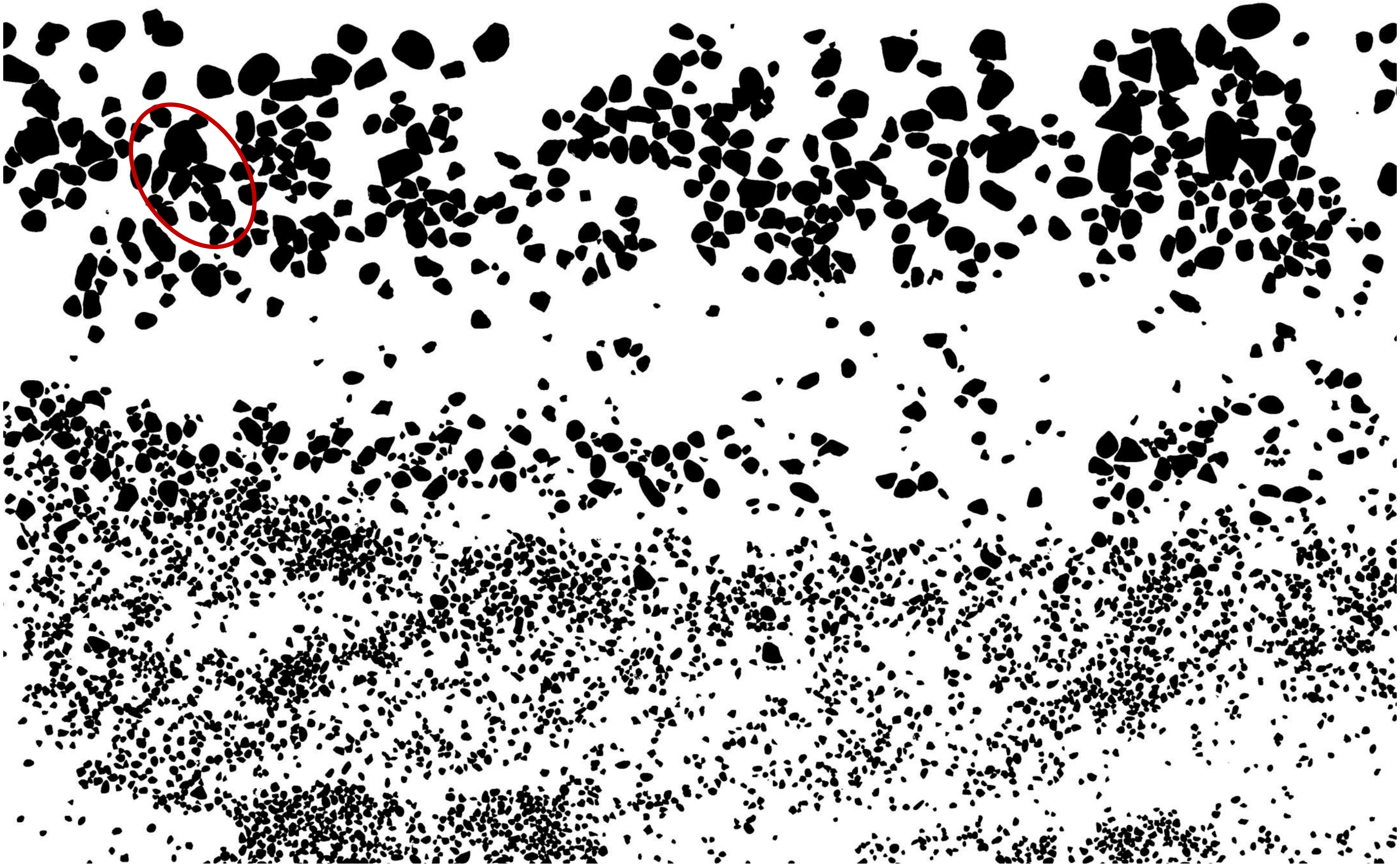


Fig. 1.14 The thresholded (black & white) image; note that particles may be in contact.

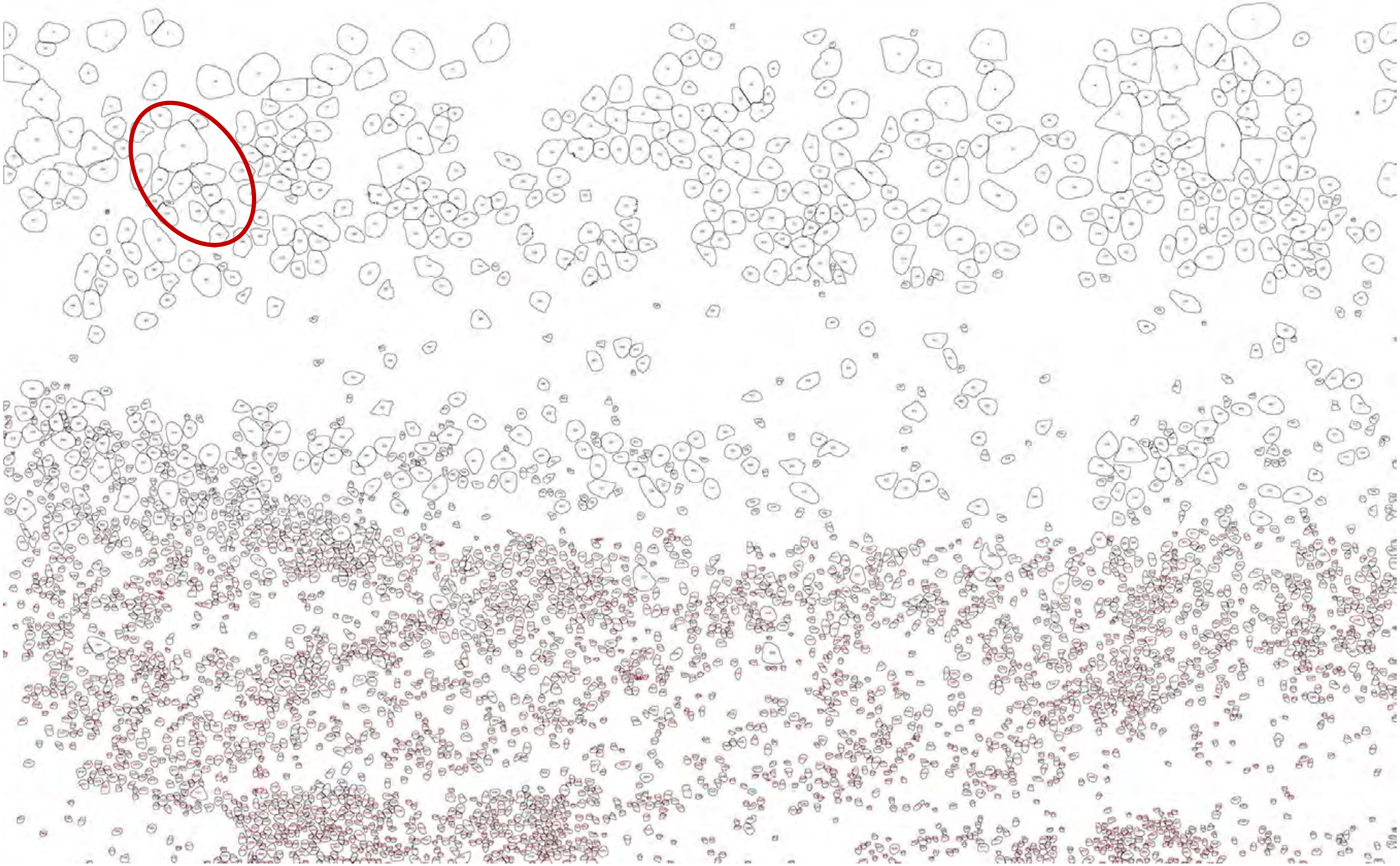


Fig. 1.15 Watershed segmentation identifies all particle edges.

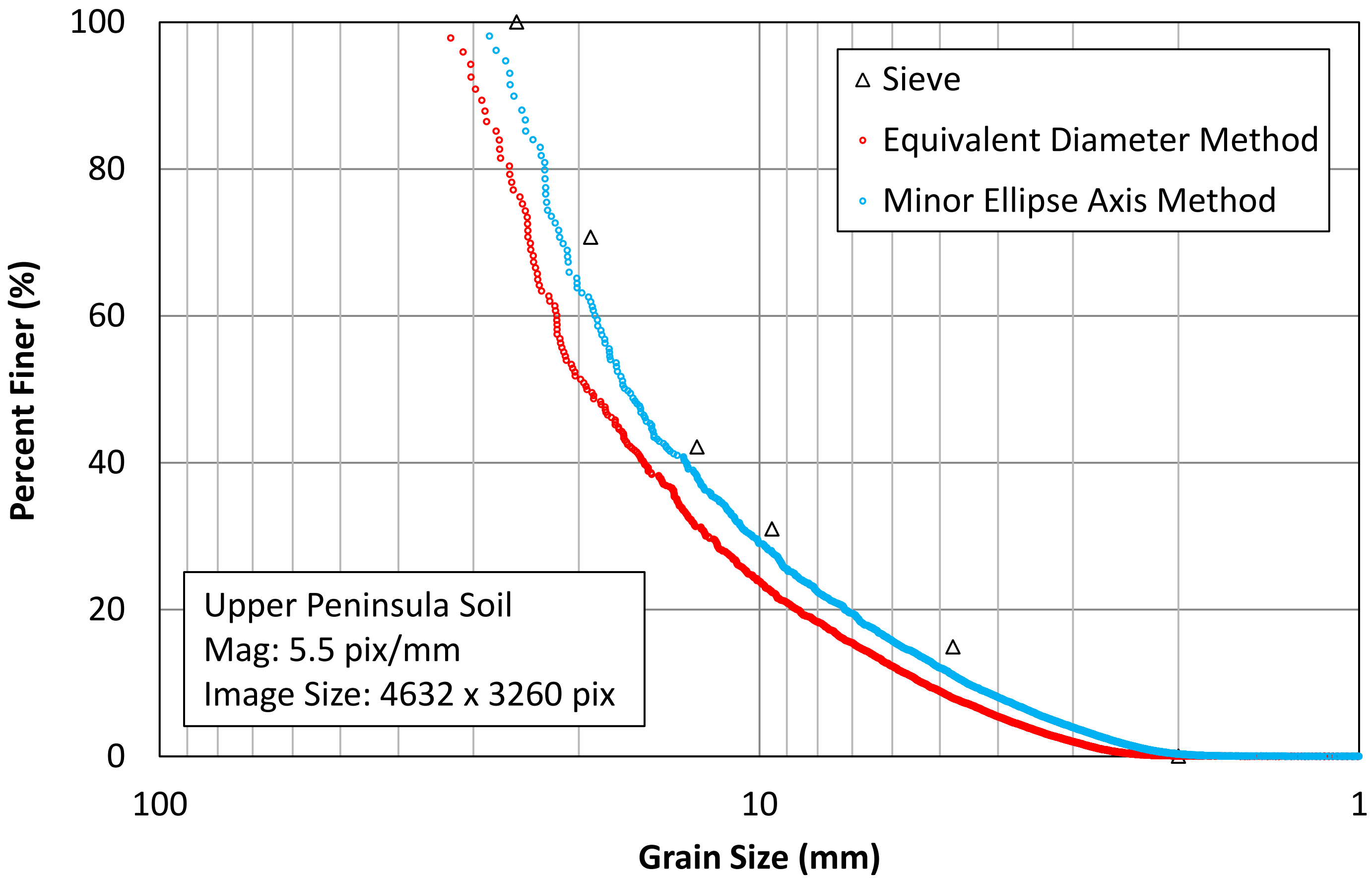


Fig. 1.16 Comparison of TST and sieve test results.

2. SEDIMAGING THEORETICAL CONCEPTS

2.1 Pixels Per Diameter (*PPD*)

In image processing and interpretation, knowledge of the scale of the photograph (or magnification) is essential to determine the size of features in the image. For soil grain size determination, units of image pixels per millimeter are most convenient. Secondly, the image features (soil particles) must be measured in units of image pixels. In this regard, the concept of the *average number of pixels per particle diameter* (*PPD*) as developed by Ghalib et al. (1998) is most useful. The *PPD* concept is illustrated in Figure 2.1. If image processing can determine the *PPD* of a soil particle assembly as discussed in Section 2.2 and the particles are all approximately the same size, then dividing the *PPD* by the image magnification yields the actual average grain size.

2.2 Wavelet Index (*CA*)

Wavelet mathematics is a relatively new field in mathematics which nevertheless traces its origins to Harr (1910). It was largely unused and forgotten until the 1970's. Wavelet transforms possess similarities to Fourier Transforms but holds one major advantage in that both the spatial and frequency information of the original signal (or image) is preserved and can be reconstructed. In other words, wavelet transforms are fully reversible and the original image may be recreated from its wavelet transform even though the transform is stored in a very compact form. The original Harr wavelet transform is used for image processing in Sedimaging. A comprehensive description of wavelet transformation can be found in many textbooks including Nievergelt (1999). As such, an abbreviated version is written here to provide the user with only a general understanding of the method. The Sedimaging program performs all of the wavelet operations in the background with no user input required.

An image to be analyzed by the Harr wavelet transformation must have 2^n pixel rows by 2^n pixel columns where n is any integer. The original image is decomposed into *n* constituent images of geometrically increasing pixel size: At the first level, each 2 pixel x 2 pixel region in an image is replaced by the difference of the pixel gray scale values of the 4 pixels. At the second level, each 4 pixel x 4 pixel region is replaced by the difference of the average pixel gray scale values of four 2 pixel x 2 pixel regions, and so on. Consequently, the size of an image will be halved at each decomposition level. The "*Energy*" at each decomposition level is then computed. This *Energy* is related to the magnitude of the differences between average gray scale values of the pixelized regions. For example, a high *Energy* at the 4th decomposition level would mean large differences between the average gray scale values of adjoining four 8 pixel x 8 pixel regions (overall 16 pixel x 16 pixel region). If the gray scale value differences between adjacent pixelized regions is small at a particular decomposition level then the associated *Energy* of the decomposition level is low. Eight successive levels of wavelet decomposition for a 256 x 256 image are shown in Figure 2.2. The energy will be highest at the decomposition level that visually appears most similar to the original image which in Fig. 2.2 would be level 3 or level 4. Shin and Hryciw (2004) found that by dividing (normalizing) the *Energies* at all decomposition levels (8 levels for a 256 x 256 image) by the sum of the energies at all levels, the effects of light illumination and soil particle color can be eliminated.

Figure 2.3 shows the *Normalized Energy* Distribution versus decomposition level for soil specimens of various *PPD*. As expected, as *PPD* increases the *Energy* shifts to higher decomposition levels. Shin and Hryciw (2004) showed that the first moment of the area beneath a normalized energy distribution correlates exceptionally well with *PPD*. The first moment was therefore defined as a *dimensionless wavelet index* (*CA*). As such, through a calibration curve of *CA* versus *PPD* which is developed on very uniform specimens of pre-sieved soils, the average grain size in the image can be determined. The most recent *CA* versus *PPD* calibration curve is shown in Figure 2.4.

2.3 The Universal Image-Based Particle Size Equation

For the majority of natural soils the relationship between *CA* and *PPD* shown in Figure 2.4 may be expressed by:

$$PPD = \left(\frac{CA + T}{2.4} \right)^{A} \tag{2.1}$$

where *T* is a particle texture index and *A* is a test condition parameter. For the majority of soils, when the particles are smooth and not mottled, *T*=0. The exponent *A* = 5.1 for saturated soils behind a 0.125 in glass pane. For dry soils, *A* can have higher values as shown in Figure 2.5 but since Sedimaging images are always taken of saturated soil behind 0.125 in thick glass, *A* is always 5.1.

Figure 2.6 shows approximate agreement between sieve and sedimaging results for typical (*T*=0) soils. Based on a limited number of tests, for rough, pitted or mottled particles T = 0.25 is tentatively recommended. Figure 2.7 shows the improved fit to sieve data when T= 0.25 is used for MDOT's 30A soil, a pitted and mottled soil.

For highly unusual soils, particularly artificial soils or soils containing minerals of distinctly different specific gravities, it may be necessary to create a soil-specific calibration curve. The user is encouraged to contact the University of Michigan Geotechnical Engineering group which can provide such soil-specific calibrations.

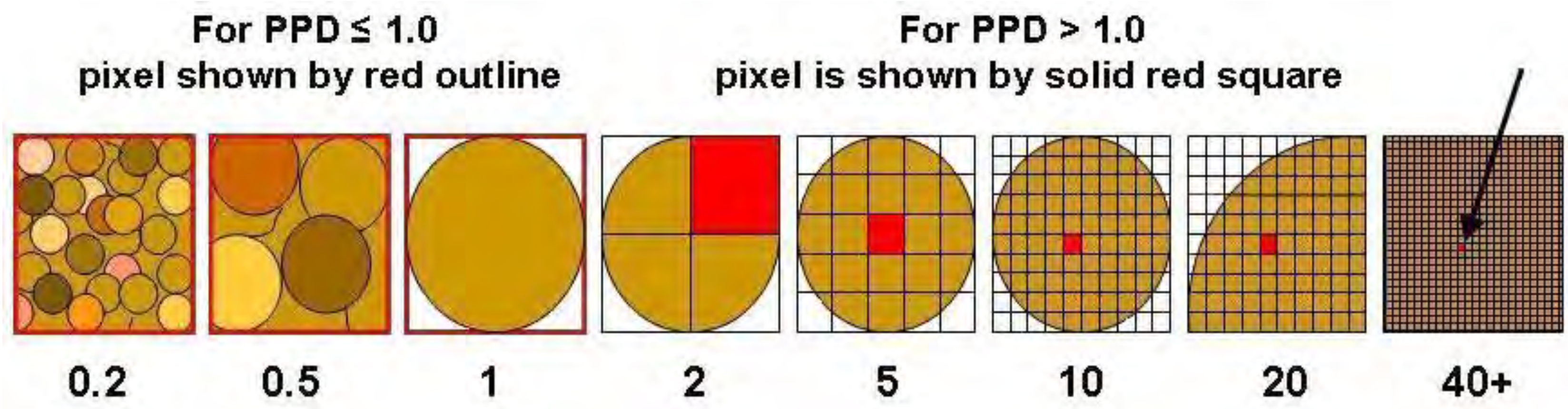


Fig. 2.1 Pixels Per Diameter (*PPD*) defined.

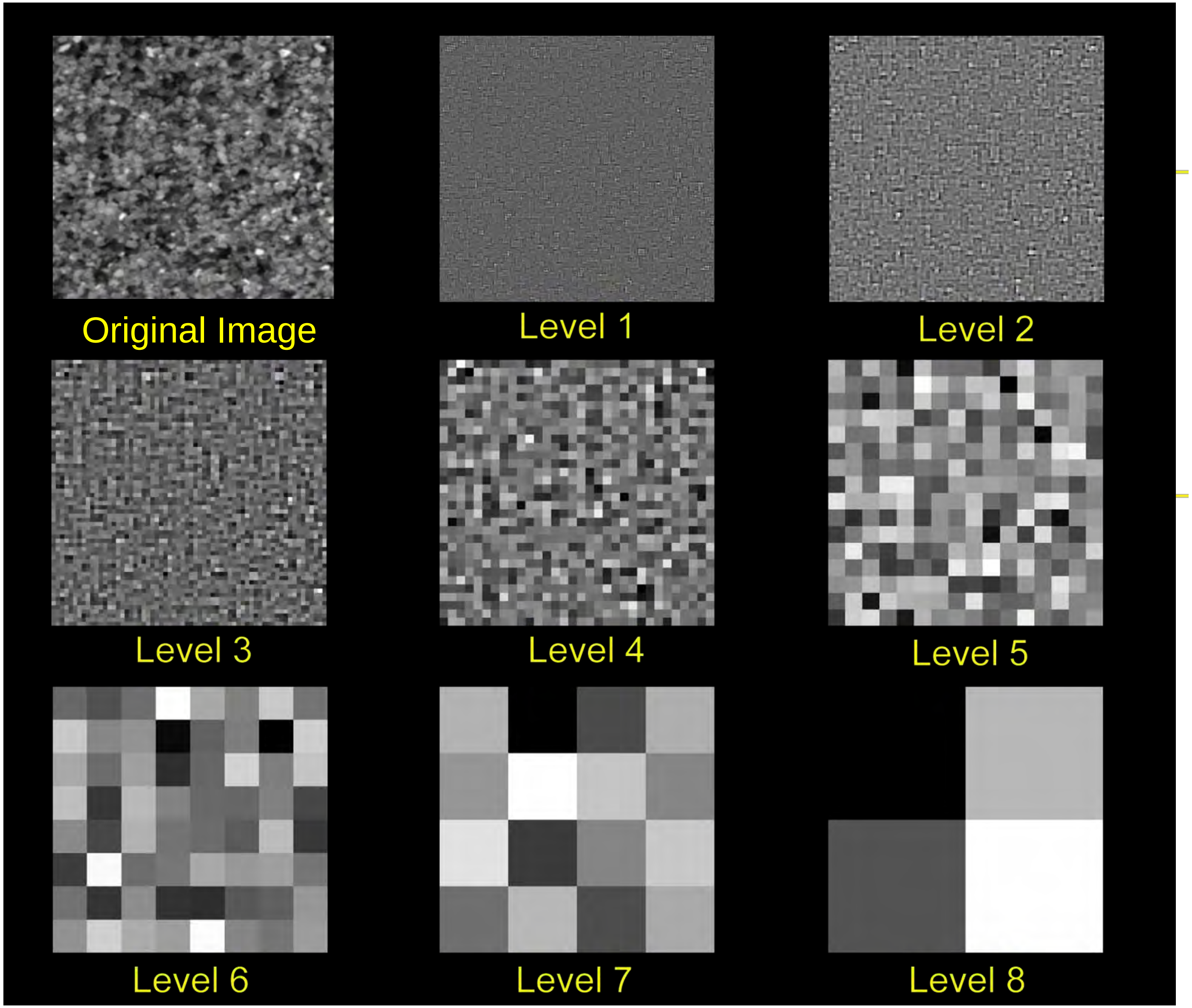


Fig. 2.2 Harr (1910) wavelet decomposition of a 256 x 256 pixel image.

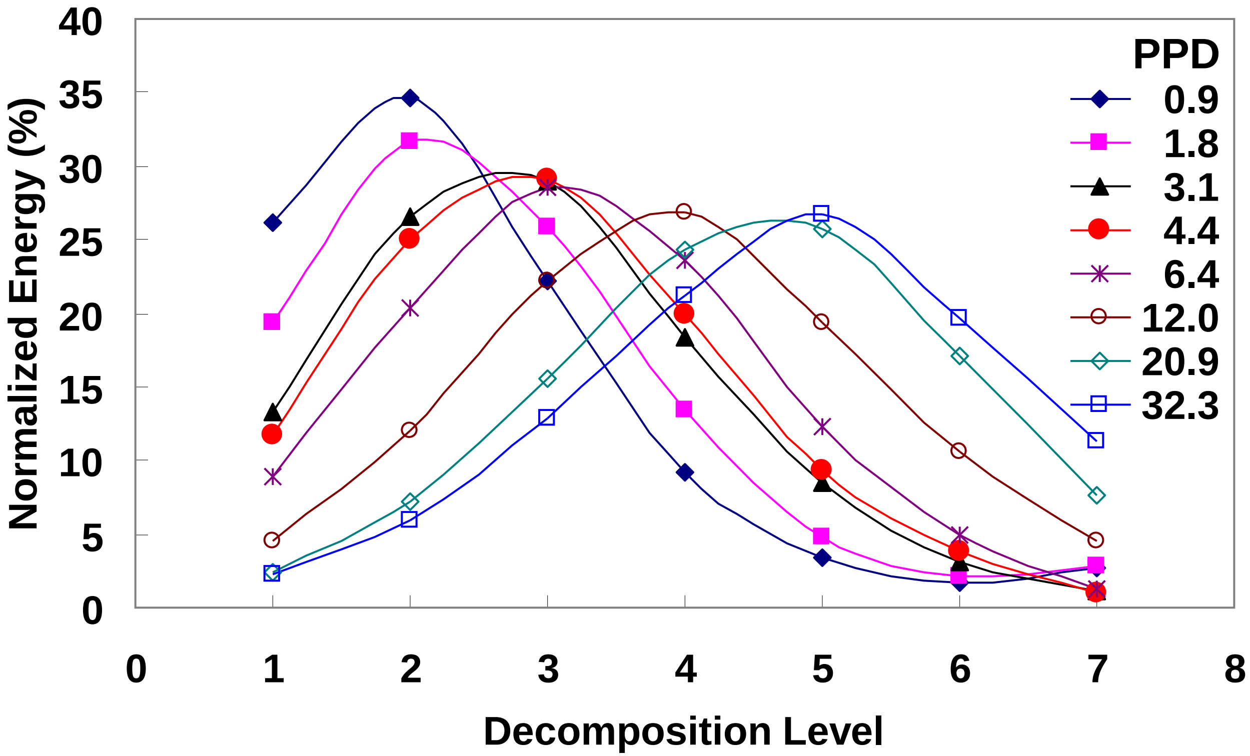


Fig. 2.3 Normalized energy vs. wavelet decomposition level for various *PPD*.

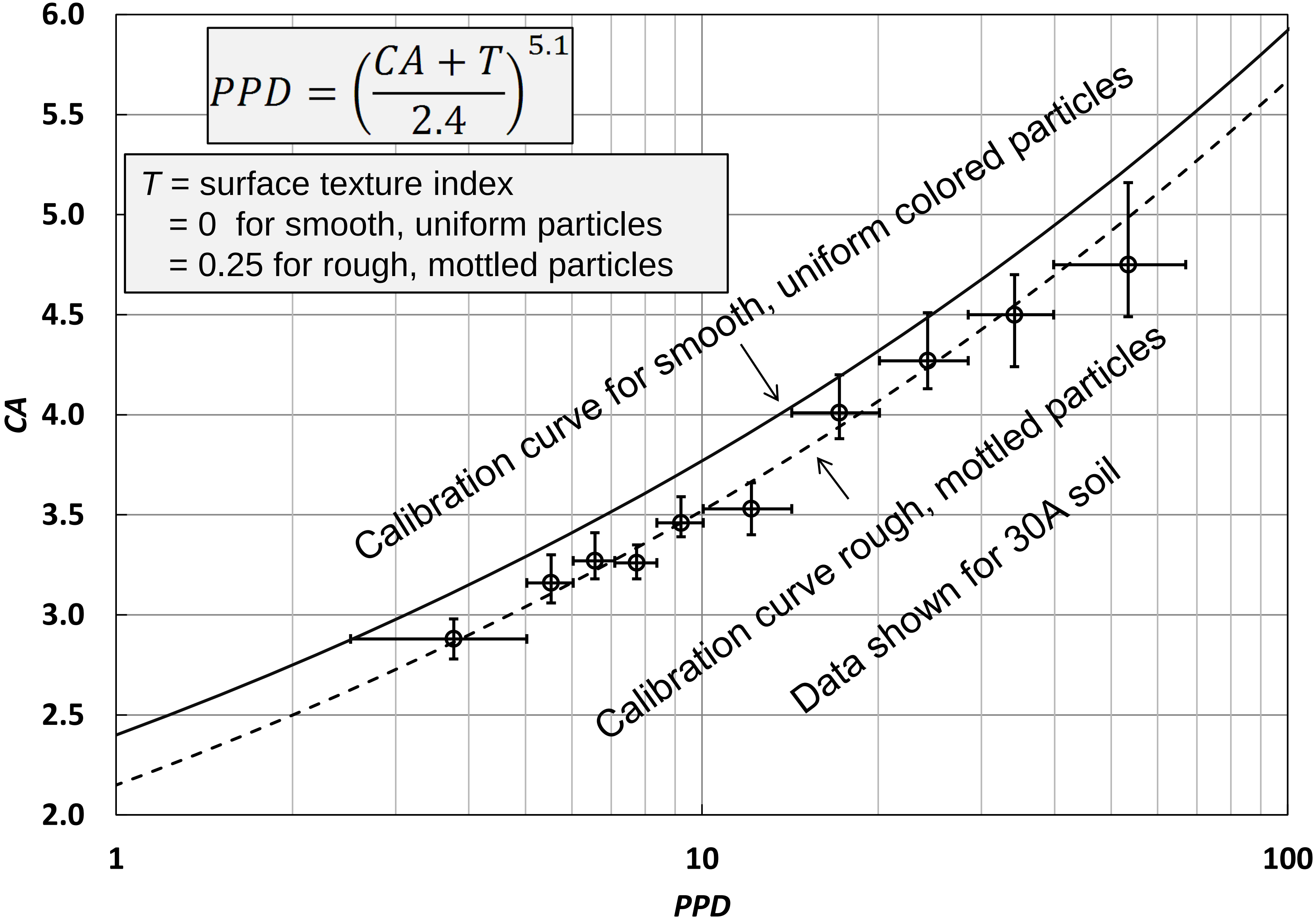


Fig. 2.4 Soil grain size calibrations for *T*=0 and *T*=0.25.

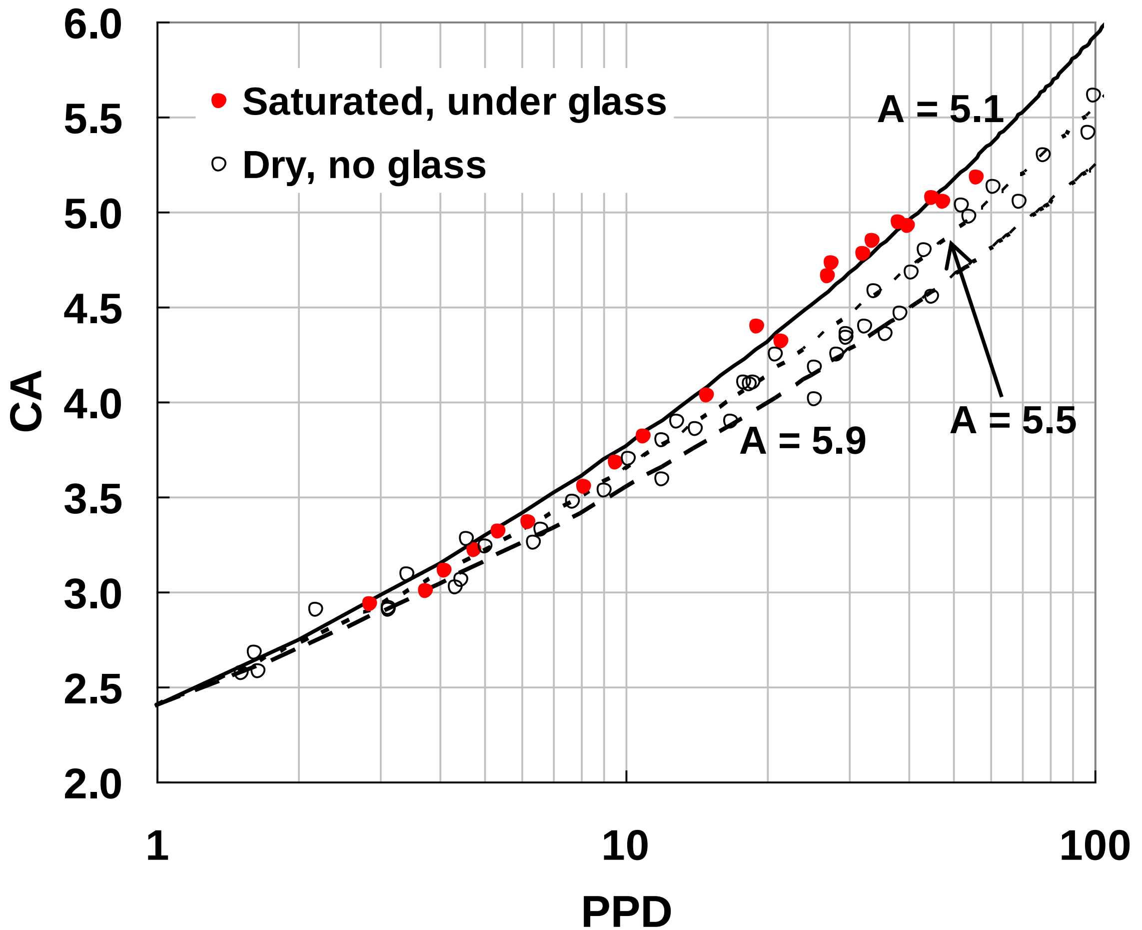


Fig. 2.5 Soil grain size calibration for saturated soils.

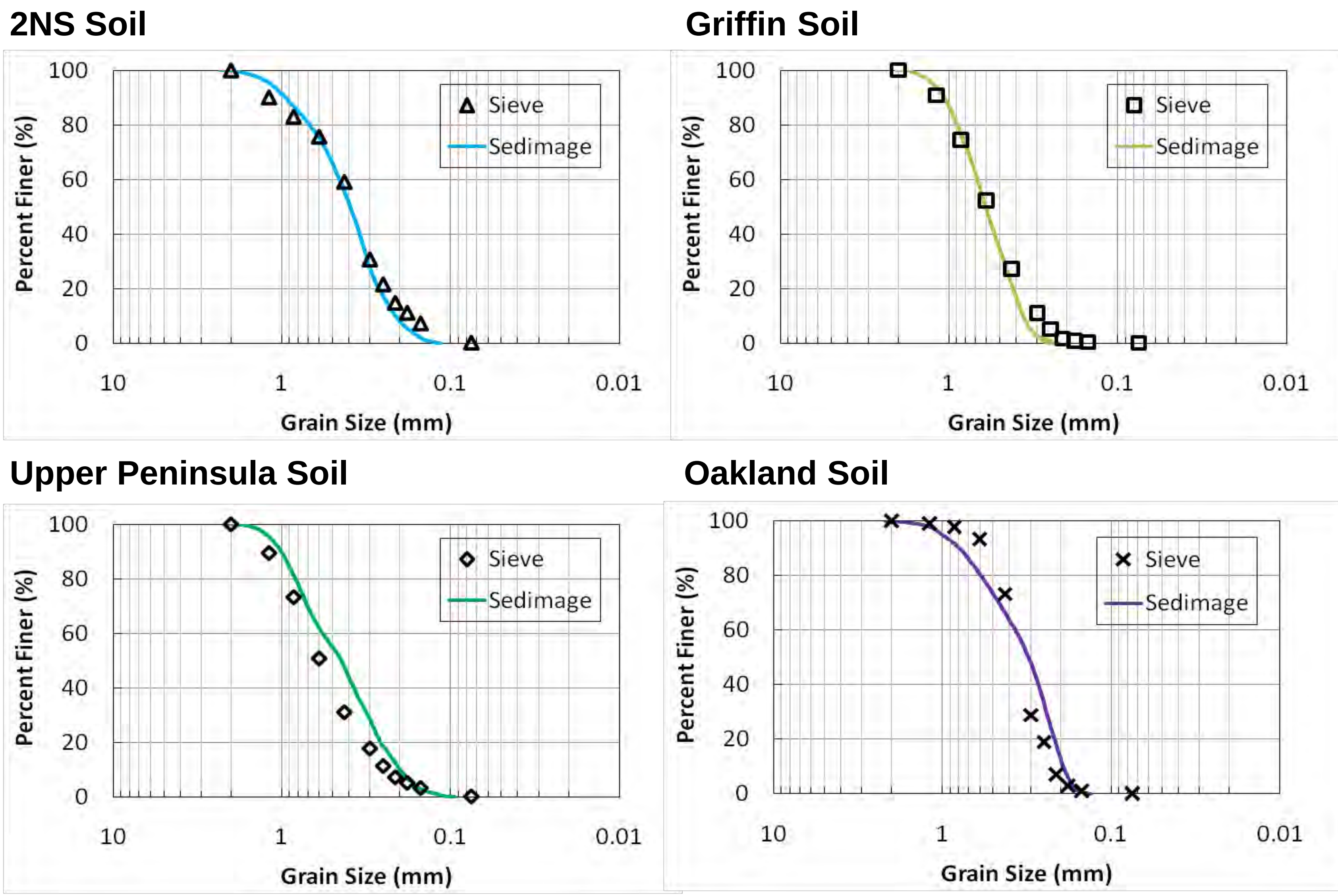
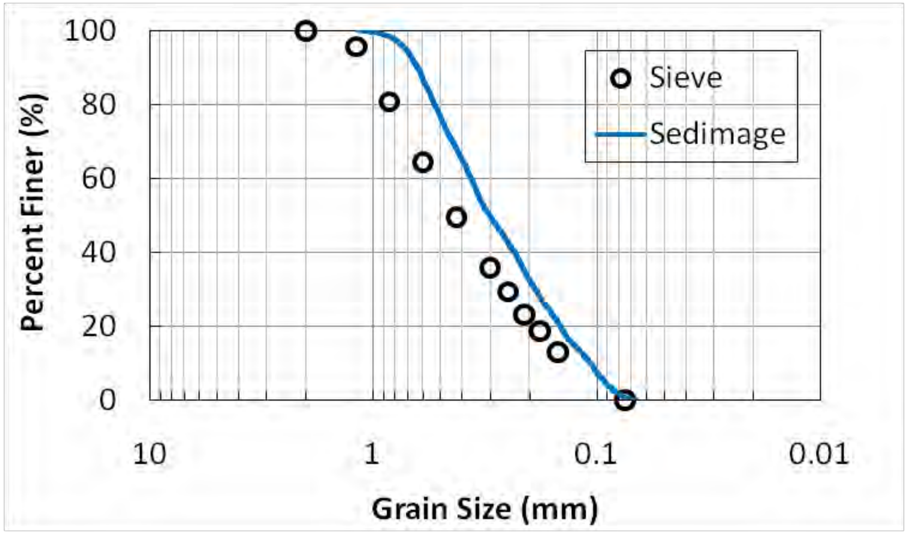
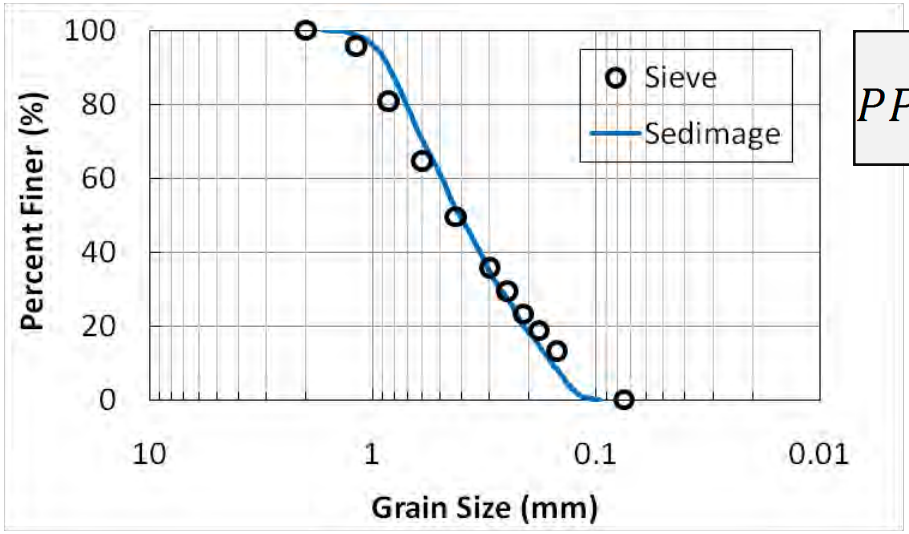


Fig. 2.6 Comparison of sedimaging and sieving results.

30A Soil T = 0



30A Soil T = 0.25



$$PPD = \left(\frac{CA + T}{2.4}\right)^{5.1}$$

Fig. 2.7 Soil grain size calibration for 30A soil with assumed *T*=0 and *T*=0.25.