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# **AC 2011-779: X-RAY COMPUTED TOMOGRAPHY: A NEW PEDAGOGICAL TOOL FOR STUDYING MICRO AND MACRO GEOMATERIAL PROPERTIES**

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# **X-Ray Computed Tomography: A New Pedagogical Tool for Studying Micro and Macro Geomaterial Properties**

## **Abstract**

Civil engineering students learn about basic geomaterial properties in the introductory geotechnical engineering or soil mechanics course, which is typically taken during the junior year of the Bachelor of Science degree program. Introductory soils courses most often include laboratory sessions in which students conduct simple destructive tests such as sieve analyses, Atterberg limits, and compaction tests. Unfortunately, there is no standardized or readily implementable test for evaluating the engineering influence and significance of soil fabric and micro properties. Textbooks and instructors emphasize the importance of soil texture, void ratio, porosity, and phase relationships; however, students often struggle with the physical meaning and significance of these fundamentally important parameters. Introducing geo-students to x-ray computed tomography (x-ray CT) helps alleviate a common issue in the geotechnical discipline; which is, some students lose interest early in the semester because of the simple, low-tech (crude), testing that is typically conducted during the first few weeks in introductory soils courses. The high-tech flavor of x-ray CT can be attractive to these students. An additional attribute of this approach is that the procedures described herein can be implemented for teaching purposes using open domain software and scanned digital images. Consequently, these experiments can be implemented by engineering departments regardless of their accessibility to an x-ray CT scanner.

## **Introduction**

This paper presents a novel approach for implementing x-ray computed tomography (x-ray CT) into an introductory soil mechanics course. Non-destructive systematic methods are described for incorporating x-ray CT into an introductory soils course to quantify microscale measurements of solid particles and void space using scanned digital images. Introducing geo-students to x-ray CT technology helps alleviate a common issue in the geotechnical discipline; which is, some students lose interest early in the semester because of the simple, low-tech, testing that is typically conducted during the first few weeks in introductory soils courses. The high-tech flavor of x-ray CT can be attractive to these students. An additional attribute of this approach is that the procedures described herein can be implemented at a relatively minimal cost using open domain software and scanned digital images.

The objective of the exercise is to help students better visualize and understand fundamental soil attributes including void ratio, gradation, and porosity in a learning environment that may be more attractive or customary to new engineers growing up in a digital age. Students are introduced to a relatively new technology that allows visualization of the internal structure of objects – a launching point for combining visualization and simulation with physical measurements and perhaps analytical or numerical modeling. The objective is not to provide detailed tomographic or radiologic training, but rather to focus on applications that are useful in the geo-industry.

This paper provides a brief overview of x-ray technology followed by a detailed description of a novel pedagogical application of this technology. The newness of this approach precludes the presentation of statistical assessments. However, anecdotal comments from students using this approach have been positive and encouraging. A more quantitative assessment of student learning will be assembled in future semesters based on a compilation of student feedback using written surveys and questionnaires.

## **Background**

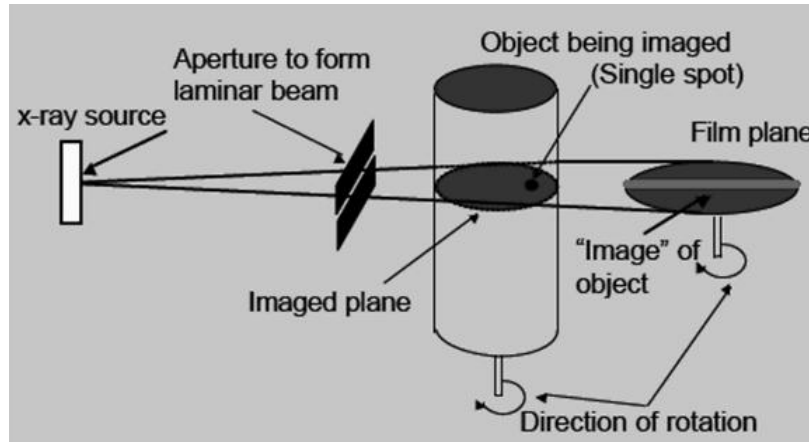
The mechanical behavior of granular soils is highly dependent on the particle microstructure. The microstructure is commonly referred to as the soil fabric, which includes the shape, distribution, and arrangement of particles and void space. Because of the inherent difficulties in measuring soil properties on a microscale, geotechnical engineers use macro properties to estimate, or predict, the response of soil when subjected to changes in the state of stress. These macro properties (void ratio, porosity, density, uniformity, etc.) are used to represent gross or average measures of the soil microstructure in terms of engineering behavior; i.e., strength, compressibility, and permeability.

The non-destructive nature of CT scanning allows the same soil or rock sample (geomaterial) to be scanned multiple times. Because the soil structure is not affected by the procedure, CT scanning provides an opportunity to investigate particle and pore characteristics at any time and location within a sample. High quality digital images can be obtained of the microstructure during loading or during environmental changes, such as fluctuations in temperatures or moisture. Tomographic studies on geomaterials conducted during the past two decades<sup>(1, 2, 3, 4)</sup> indicate that x-ray CT technology provides a viable means for nondestructively observing, measuring, and quantifying the internal microstructure of geomaterials.

X-ray computer-aided tomography (CT) provides an alternate approach for measuring soil microstructure. An x-ray CT scan consists of two processes: 1) data collection and 2) image reconstruction. During the data collection stage, a specimen is digitally photographed from multiple angles as it is exposed to x-ray beams. X-rays are invisible, high-energy electromagnetic waves that are able to pass through many objects. X-rays that penetrate an object will encounter an x-ray sensitive screen within the CT apparatus and cause it to illuminate. During x-ray exposure, the object's matter will absorb some of the x-rays and the intensity (energy per unit area per unit time) of the x-ray will attenuate as it is absorbed and scattered by the atoms of the material. A material with high density will attenuate more x-rays than a low-density material; therefore, two materials of different densities will appear differently in an x-ray image. This allows the distinction between different phases of material in a soil specimen; i.e., mineral particles, water-filled voids, and air-filled voids may each appear distinct within an x-ray image.

A digital camera is used to capture the image on a luminescent phosphor screen, which replicates the x-ray penetration pattern of the object. The pixel intensity (gray-scale shade) in the CT image provides a measure of total attenuation, which is a combination of the mass attenuation and mass density of the material. This attenuation is quantified using the linear attenuation coefficient<sup>(5)</sup>. In terms of CT imaging technology, the linear attenuation coefficient is related to the density of a pixel and is useful for distinguishing and quantifying different constituents of a

specimen. A typical x-ray equipment configuration for what is known in the industry as a third generation fan beam scanner is shown in Fig. 1.



**FIGURE 1. Typical laboratory x-ray configuration<sup>(6)</sup>.**

During the image reconstruction phase, photographs of multiple x-ray scans are digitally superimposed in such a way that the resulting image describes the interior structure and features of the specimen. When the scan is reconstructed, the resulting image is a cross-sectional view of the object as if it had been cut through the plane at the scan location. The CT scanning equipment at the author's university is capable of performing scans at increments as small as 1/8-degree of rotation. The author's system, similar to that shown in Fig. 6, is a 2-dimensional (2-D) system, which can be used to create a 3-dimensional (3-D) image by combining multiple images (slices). Newer generation 3-D systems are available that can be used to capture a full, high resolution, 3-D image of a geo-sample with one scan. Similar 3-D equipment is used in the medical industry; although, higher x-ray energies are used when scanning geomaterials to improve the resolution of these particles, which have higher attenuation factors than tissue and organs in the human body.

### **Basics of X-ray Image Processing and Reconstruction**

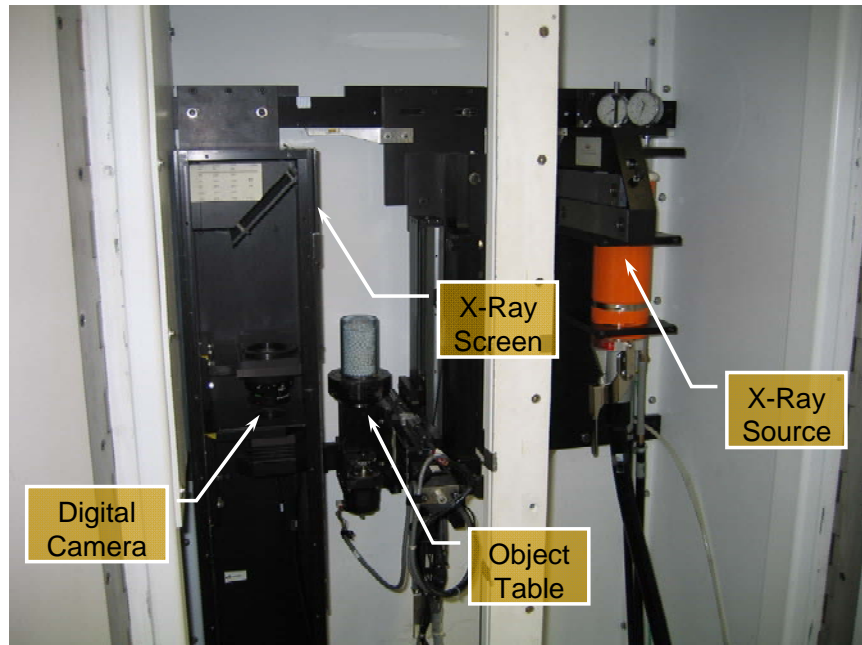
After a sample is scanned, the recorded data is assimilated into a meaningful digital representation using computer-based algorithms. Converting recorded x-ray data into a digital image is one of the primary functions of computed tomography. A reconstructed tomographic data file provides a quantifiable description of solid particles and void spaces in a series of two-dimensional cross-sectional images, which also can be combined together to create a three dimensional volume view of the scanned object<sup>(7)</sup>. Each pixel of a scanned image represents the average density of a voxel (volumetric representation of a pixel) at a particular (x, y) location. By combining many images obtained at close spacings, a quantifiable estimate of the void space, porosity, or solid particulate distribution can be obtained. Image processing can be conducted using a variety of commercially available software packages. The approaches described in this paper utilize the open source software titled *ImageJ*, which is an image analysis program

originally developed by scientists from the National Institutes of Health. The software can be downloaded from the developer's website along with numerous 'plug-in' subroutines that provide enhanced image reconstruction and processing applications.

Digital images suitable for collecting information about the internal structure of a soil sample can be used for making quantifiable measurements of basic properties such as void ratio, porosity, density, and grain size. These properties are calculated from a raw CT image using a series of steps that can be categorized under the following three headings: 1) filtering, 2) thresholding, and 3) measuring and digitizing the image. Background and information regarding these steps are described in detail by Nielsen and Mokwa<sup>(8)</sup>. This paper focuses on the applications after an array of digitally recorded x-ray data (sinogram) is assembled and reconstructed into a cross-sectional slice (tomogram).

### **Preliminary Steps for Developing a Working Digital Image**

Prior to obtaining a digital image, the sample must be sized and prepared for the x-ray scanner. Soil samples are typically placed in a stiff-walled plastic container by either raining or fluviation methods or by placing the soil in layers and compacting using controlled repeatable dynamic impacts from a rammer or weight. Rock cores should have a flat smooth end to minimize wobbling and eccentricities if the scanner contains an internal platen that rotates during scanning. Even snow and ice samples can be scanned for useful measurements; however, these sensitive materials require extra preparation steps and of course must be prepared and tested at sub-freezing temperatures. The scanner at the authors' university was constructed to work with an internal chilling unit. Some smaller scanners can be placed entirely in a climate controlled cold room for this purpose. Figure 2 shows a cylindrical sample inside our x-ray scanner.



**FIGURE 2. Interior view of x-ray scanner equipment.**

The sample is placed in the device and exposed to high energy electromagnetic waves (x-rays). The severity of x-ray attenuation is a function of the thickness and density of the material. The intensity of the emerging x-ray beam is measured and digitally recorded. Raw data files created during the scanning process are converted to a file with a Dicom file extension, which is an acronym for Digital Imaging and Communications in Medicine Format.

The basic (simplified) steps described in the previous paragraph can be explained to the students with as much, or little, detail as necessary depending on available time in the class schedule. The hands-on aspect of this exercise begins with either a Dicom file obtained with the CT reconstruction software, or simply a jpeg file of the CT image (or even a photograph). Either file types are readily input into *ImageJ* for editing, manipulating, and analyzing electronic images of the scanned samples. The Dicom option is especially useful for evaluating a stack of multiple images (slices) at one time. The advantage of jpeg files is they are more readily available and do not require CT reconstruction software. The following paragraphs provide a step-by-step outline that can be implemented in an introductory geotechnical engineering or soil mechanics course.

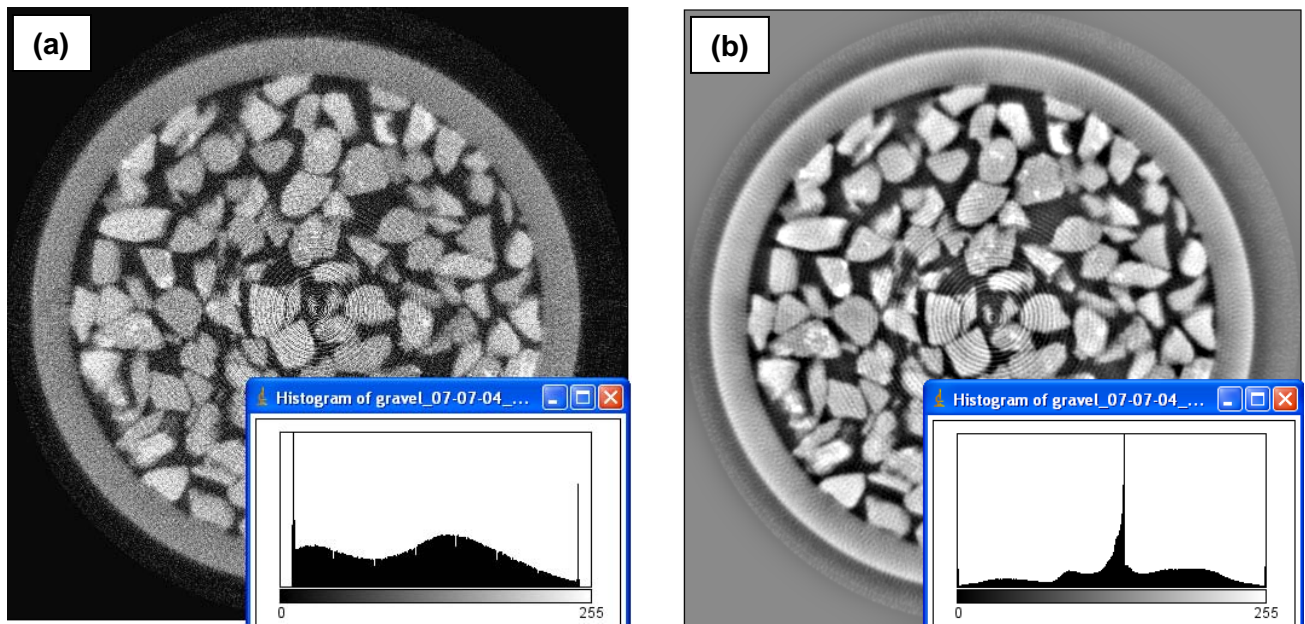
### **Step 1.**

Open ImageJ and click the *File* tab, then *Open*. Select (double click) the appropriate jpeg file that contains an image of a scanned 2-D slice. Alternately, if a series of images is available, click *File, Import, Image Sequence*, and double-click on the first file. This will automatically load the series (stack) of files. An image similar to the gravel slice shown in Fig. 3a will appear on the computer screen.

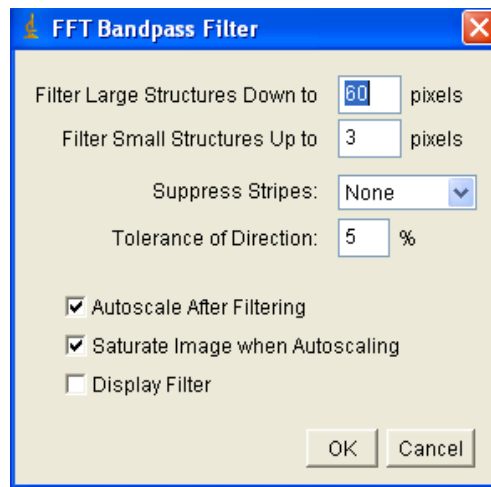
### **Step 2.**

This step invokes a filter in ImageJ that removes background noise from the image by applying a pixel shading correction and a smoothing feature. In addition to improving image clarity and contrast, the filter allows for an easier and more accurate manual selection of a threshold value from the image histogram. Figure 3a shows the unfiltered image and corresponding histogram. Fig. 3b shows the same image and corresponding revised histogram after the Bandpass filter is applied.

Select the *Process* tab, *FFT* option, and *Bandpass Filter* option. Start with the settings shown in Fig. 4, which are often reasonable for sand to gravel size particles based on multiple comparison analyses by the authors. These settings would be a good starting point for any geomaterial; however, the accuracy can be improved by further optimizing the settings through trial and error.



**FIGURE 3.** A 2-D x-ray CT image of gravel: a) original image as imported into ImageJ and corresponding histogram, b) image after Bandpass Filter processing and corresponding histogram.



**FIGURE 4.** Screen shot for suggested initial settings for Bandpass Filter option.

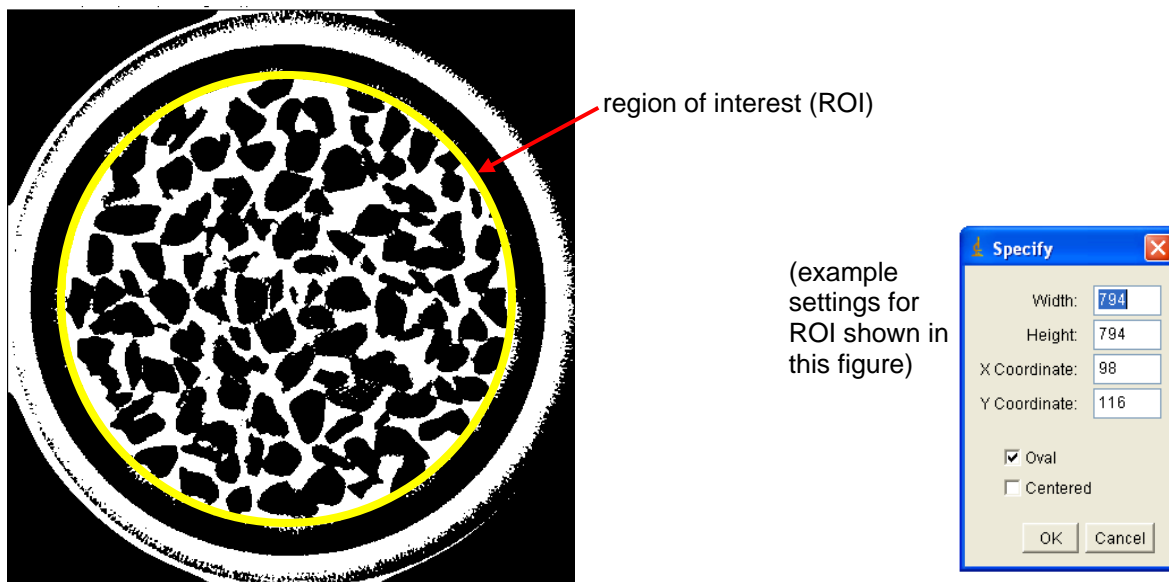
### Step 3.

For an 8-bit image, there are 255 different pixel intensity values ranging from gray scale intensity 255 to gray scale intensity 0. Image thresholding, also called binarization, is a segmentation process in which the gray scale boundary between particles of solid matter and void space is identified using a histogram. Properties of the image can be quantified after a void/solid gray scale boundary (threshold) is determined. In this step, the image is converted into binary format using the selected threshold value.

Select the *Image* tab, *Adjust* option, and *Threshold* option. This option allows the user to manually select a threshold and convert the image into binary format. The threshold window displays two sliders directly below the histogram. Move the bottom slider to the far right position (setting 255) and then move the top slider to a reasonable location by observing changes in the solid particles and void spaces in the 2-D image slice. Based on the authors experience with a variety of geomaterials, a reasonable threshold value typically occurs a small distance to the left of the peak in the pixel distribution histogram. As a point of comparison, Temmyo and Obara<sup>(9)</sup> recommend selecting the point of maximum curvature located on the upper left half of the histogram. After selecting a reasonable value, click *Apply*. The image is now in a binary format and ready for analysis.

### Step 4.

This step involves selecting the region of interest (ROI) for subsequent analysis by eliminating extraneous data beyond the edge of the sample. Select the *Analyze* tab, *Tools* option, *ROI Manager* option, *More* tab (last tab in the list), and *Specify* option. Select *Oval* and then *OK*. A yellow oval-shaped line will appear. Use the small tabs to size the oval to encompass the sample by sizing and positioning the oval just inside of the dark ring that represents the sample container, as shown in Fig. 5.



**FIGURE 5.** Screen shot showing the region of interest superimposed on the binary image.



### Step 5.

The void ratio and porosity are calculated in this step. In geotechnical engineering, the void ratio ( $e$ ) is defined as:

$$e = \frac{\text{Volume of voids}}{\text{Volume of solids}} = \frac{V_v}{V_s} \quad (1)$$

The porosity ( $n$ ) is defined as:

$$n = \frac{\text{Volume of voids}}{\text{Total Volume}} \times 100\% = \frac{V_v}{V_t} \times 100\% \quad (2)$$

Void ratio and porosity are related by:

$$e = \frac{n}{1-n} \quad \text{or} \quad n = \frac{e}{1+e} \quad (3)$$

The void ratio and porosity of the scanned image are determined using area measurements from the binary image that was created in the previous steps. Select the *Analyze* tab and *Histogram* option. Select the *List* button from the bottom of the window and record the pixel counts at the gray scale value of 0 and 255. Using the approach described in this paper, the value at 0 gray scale corresponds to the area of void space in square pixels and the value at 255 corresponds to the area of solid particles in square pixels. Thus,  $e$  is calculated as:

$$e = \frac{(\text{count at pixel value} = 0)}{(\text{count at pixel value} = 255)} \quad (4)$$

Porosity is calculated as:

$$n = \frac{(\text{count at pixel value} = 0)}{(\text{count at pixel value} = 0) + (\text{count at pixel value} = 255)} \times 100\% \quad (5)$$

### Step 6.

This step is used to develop a grain size distribution curve for the sample as represented by a slice or stack of slices. Select the *Analyze* tab, *Analyze Particles* option, and input the options shown in Fig. 6, then click *OK*. In the results window that appears, select the *File* tab and *Save As* option. Save the spreadsheet file that is automatically created in a convenient folder. The area column in the spreadsheet provides the area of each particle in square pixels, which is converted into square mm as follows:

$$\text{area of particle in (mm)}^2 = (\text{area in pixels}) \times \left[ \frac{(\text{container outer diameter in mm})}{(\text{container outer diameter in pixels})} \right]^2 \quad (6)$$

The Schedule 40 PVC sample container used by the authors had an outer diameter of 60.325 mm. The container outside diameter based on the digital image was 908 pixels, which is determined by locating the cursor on the outer ring along two diametrically opposite points and taking the difference of the x-values shown on the screen. The size of each particle, based on the area of a square, is calculated by taking the square root of the area that was determined using Eq. 6.



## **Pore Size Distribution**

The pore size distribution can also be approximated using this same approach by inverting the histogram/thresholding procedure and creating a bimodal image in which black (255 gray scale) represents voids and white (0 gray scale) represents solids. The true pore size distribution is quite complex and not easily measured because of the influence of tortuosity and connectivity of void space. For example, a soil with low pore connectivity will measure differently than a soil with high connectivity, even if the pores have the same characteristic size<sup>(10)</sup>. Most experimental methods for measuring pore size distribution work on the fundamental principles of capillary pressure and related pore suction pressures. Traditional experimental methods, including mercury intrusion and pressure plate suction (tensiometry) tests, are not highly accurate and often yield inconsistent results<sup>(11)</sup>. These methods tend to introduce testing bias in which the test procedures destroy or alter the same parameters they purport to measure. Because of these complexities, there is no benchmark test for measuring pore size distribution. Additional research and verification of pore size distributions from x-ray CT is necessary before the results are extended to practical applications. Nevertheless, if the grain size distribution from x-ray CT matches results from mechanical sieve analyses, then it can be reasonably assumed the pore size distribution is at least suitable for relative comparative purposes.

## **Summary and Conclusions**

Civil engineering students learn about basic geomaterial properties in the introductory geotechnical engineering or soil mechanics course, which is typically taken during the junior year of the Bachelor of Science degree program. Introductory soils courses most often include laboratory sessions in which students conduct simple destructive tests such as sieve analyses, water content, Atterberg limits, and compaction tests. Unfortunately, there is no standardized or readily implementable test for evaluating the engineering influence and significance of soil fabric and micro properties. Textbooks and lectures emphasize the importance of soil texture, void ratio, porosity, and phase relationships; however, students often struggle with the physical meaning and significance of these fundamentally important parameters.

A novel approach for implementing x-ray computed tomography (x-ray CT) in introductory soil mechanics courses was described in this paper. A systematic method was outlined for using non-destructive x-ray CT to quantify microscale measurements of void ratio, porosity, and grain size distribution of scanned digital images. Primary benefits of this approach include:

- 1) Students visually perceive and quantify relationships between particulates and voids.
- 2) Students attain a better understanding of the mechanical properties of soils through laboratory experiments that include both simple destructive empirical tests and nondestructive techniques using advanced technologies that are destined to become prevalent during their careers.
- 3) Students are excited about learning a relatively advanced technology that is readily adaptable to a wide range of cross-disciplinary applications.
- 4) The instructor can incorporate this relatively simple approach into lessons or exercises currently used for teaching soil phase relationship concepts and for solving mass-volume relationship problems.

It has been the primary author's experience that engaging geo-students in the use of x-ray CT technology helps alleviate a common issue in the geotechnical engineering discipline; which is, some students lose interest early in the semester because of the simple, low-tech, testing that is typically conducted during the first few weeks in introductory soils courses. The high-tech flavor of x-ray CT can be attractive to these students. Anecdotal comments from students using this approach have been positive and encouraging; however, the newness of this approach precludes the presentation of statistical assessments in this paper. A more quantitative assessment of student learning will be assembled in future semesters based on additional student feedback.

### **Acknowledgements**

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### **References Cited**

1. Alshibli, K. A., Batiste, S. N., Swanson, R. A., Sture, S., Costes, N. C., and Lankton, M. R. (2000). Quantifying Void Ratio in Sand Using Computed Tomography. *ASCE Geotechnical Special Publication*, GSP 106, p. 30-43.
2. Otani, J. (2004). State of the Art Report on Geotechnical X-ray CT Research at Kumamoto University. X-ray CT for Geomaterials; Soil, Concrete, Rocks. *Proceedings of the International Workshop on X-ray CT for Geomaterials, GeoX2003*, Kumamoto, Japan, Balkema Pub, p. 43-77.
3. Mokwa, R. and B. Nielsen. (2006). Characterization of Soil Porosity Using X-ray Computed Tomography. *ASCE Geotechnical Special Publication No. 149*, Site and Geomaterial Characterization, Shanghai, China, p. 96-103.
4. Wang, L., C. Druta, Y. Zhou, and C. Harris. (2010). 3D Aggregate Evaluation Using Laser and X-ray Scanning. *Advances in Computed Tomography for Geomaterials, GeoX2010*, New Orleans, LA, Wiley Pub, p. 101-107.
5. Phillips, D. H. and Lannutti, J. J. (1997). Measuring Physical Density with X-Ray Computed Tomography. *NDT & E International*, vol. 30(6), p. 339-350.
6. Peters, T. (2002). CT Image Reconstruction, Retrieved April 19, 2010 from [www.aapm.org/meetings/02AM/pdf/8372-23331.pdf](http://www.aapm.org/meetings/02AM/pdf/8372-23331.pdf).
7. Alramahi, B. and K. Alshibli. (2006). Applications of CT to Characterize the Internal Structure of Geomaterials: Limitations and Challenges. *ASCE Geotechnical Special Publication No. 149*, Site and Geomaterial Characterization, Shanghai, China, p. 88-95.
8. Nielsen, B. D. and Mokwa, R. L. (2004). Non-Destructive Soil Testing Using X-Ray Computed Tomography. Final Research Report for the Western Transportation Institute, Bozeman, Montana, pp. 126.
9. Temmyo, T. and Y. Obara. (2010). Quantification of Material Constitution in Concrete by X-ray CT Method. *Advances in Computed Tomography for Geomaterials, GeoX2010*, New Orleans, LA, Wiley Pub, p. 140-147.
10. Vervoort, R. W. and Cattle, S. R. (2003). Linking Hydraulic Conductivity and Tortuosity Parameters to Pore Space Geometry and Pore-Size Distribution. *Journal of Hydrology*, vol. 272, p. 36-49.
11. Gaskin, P. N. and Raymond, G. P. (1973). Pore Size Distribution as a Frost Susceptibility Criterion. *Proc. of the Symposium on Frost Action on Roads*, Oslo, Norway, p. 76-78.