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Using X-ray micro CT imaging data to obtain particle morphology and soil fabric parameters

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ABSTRACT

In addition to the well-understood effects of void ratio and effective confining stress on the mechanical behavior of fine-grained soils, past experimental research at the University of British Columbia (UBC), Vancouver, Canada, has revealed a considerable effect of particle fabric on the monotonic and cyclic shear behavior of silts. With this background, an experimental research program was undertaken to further investigate the particulate nature and arrangement of silts. The fabric of soils has been traditionally associated with the matrix void ratio, but can be directly associated with fabric parameters like the coordination number. Furthermore, grain morphology has a significant impact on these characteristics. Advancements in acquiring digital images and associated processing have made it possible to obtain individual soil particle parameters such as length, width, breath, thickness, volume, etc., along with information on spatial location and orientation of a given particle - thus providing the data needed to determine contact fabric and morphology of a soil matrix. In order to calculate these parameters and look for any potential correlations, commercially available, pre-calibrated, standard-size silica having particles within the size range from 40 μm to 60 μm, were imaged and analyzed. This study establishes an approach for extracting void and morphological information from tomographic images using image analysis techniques and algorithms developed in-house. Initial observations related to particle morphology and preliminary fabric scalar parameters are discussed. This work contributes to the accounting for fabric in understanding the macroscopic shear behavior of silts from the Fraser River Delta, British Columbia, Canada.

Keywords: soil fabric/microstructure; x-ray micro-CT, fabric parameters; low plastic silts

1. Introduction

Based on prior earthquake experience (e.g., Turkey's Kocaeli earthquake in 1999 and New Zealand's Christchurch earthquake in 2010–2011), fine-grained silty soils with high saturation levels are susceptible to earthquake-induced softening and strength loss. This background has led to substantial research work on the earthquake response of low plastic silts at the University of British Columbia (UBC) in Canada. The results from this work demonstrate that the soil fabric and microstructure significantly affect the mechanical response of natural silts (Wijewickreme et al. 2019). In light of this, an experimental program was undertaken to more thoroughly comprehend the macro behaviour of silts utilising microparticle physics. The present study in progress aims to acquire three-dimensional pictures using X-ray micro-computed tomography for studying particle morphology and soil fabric. Previous studies found in the literature mainly focus on understanding the fabric of sandy materials (Hight & Leroueil 2003; Fonseca 2011). Yet, digital particle segmentation becomes more difficult and is constrained by a number of parameters, including image resolution and processing capacity, when analyzing silt size particles (ranging between 2-74 um) are involved. Owing to recent computational advances, measurement of parameters, such as length, breadth, thickness, volume, etc., essential to describe individual particles for morphological and fabric studies, are obtainable. Initial work at UBC, so far, to explore the feasibility of micro computed tomography (μ-CT) in visualizing silt sized fabric has found promising results (Wesolowski 2020; Valverde et al. 2020; Valverde & Wijewickreme 2021a; Valverde & Wijewickreme 2021b; Wijewickreme & Valverde 2022).

It is widely reported in the literature that particle morphology (i.e., size and shape) has a direct influence on the mechanical behavior of soil and forms a vital step in studying the fabric of soils (Holtz and Kovacs, 1981; Guo and Su 2007; Clayton et al. 2006). Moreover, scalar and directional fabric parameters (i.e., void ratio, coordination number, particle orientation, etc.) are used to describe the fabric and its evolution. In recent years, the available techniques and standard software applications useable for computer analysis of size and shape data by digital imaging have improved greatly. With this, it is increasingly becoming possible to investigate the key aspects of soil fabric, i.e., particle orientation, void ratios, etc., using X-ray μ-CT imaging.

In the present study, 3D images of specimens of pre-calibrated silica particles were obtained as a first approach to obtain morphological measurements and preliminary fabric parameters; this methodology will be transferrable to natural silts. As a part of analyzing the particle size distributions (PSDs) obtained from X-ray μ-CT imaging for standard-sized-grain matrices are compared with those directly available from manufacturers' calibration, laser diffraction analysis, as well as from mechanical sieving.

This paper presents an extract of the above works conducted at UBC using an X-ray µ-CT imaging-based approach to capture the fabric of silt-sized particle matrices. In this paper, imaging and segmentation procedures with respect to the above topic are assessed using commercially available, pre-calibrated, standard-size silica particles. Details with regard to the material used and the specimen preparation are first presented. This is followed by information on image acquisition, processing and analysis, and the limitations of this methodology. Moreover, details on obtaining particle size, shape, orientation and void ratios of specimens are presented. The experiments were conducted at the UBC Geotechnical Engineering Graduate laboratory and the imaging was performed in the X-ray µ-CT device at the Pulp and Paper Center in UBC Vancouver.

2. Experimental aspects

2.1. Non-destructive micro-CT imaging equipment

The X-ray µ-CT scanning undertaken herein was conducted using a ZEISS Xradia 520 Versa device, as shown in Fig. 1b, manufactured by Zeiss International, Oberkochen, Germany. This scanner restricts the movement of the source and detector allowing for greater control and more precise scanning at higher resolutions (Ketcham & Carlson 2001; Helliwell et al. 2013).

X-ray µ-CT tomography involves producing 2D images that record the variation of X-ray attenuation within objects, which relates closely to the density of the material penetrated by the X-rays. The 2D images are later stacked and reconstructed into a 3D image. The typical set up includes an X-ray source, a detector, scintillator that allows for optical magnification (which increases the potential resolution), and the rotation system in which the sample is located (Fig. 1a). A specimen holder was specifically designed and fabricated to provide a well secured soil specimens while scanning.

In order to achieve images with satisfactory resolution, several parameters need to be controlled. In this case, a field of view of ~800 µm was used for the scans that resulted in a 0.8 µm resolution. The output of a µ-CT scan requires further digital processing to perform qualitative and quantitative image analysis as explained in section 3.

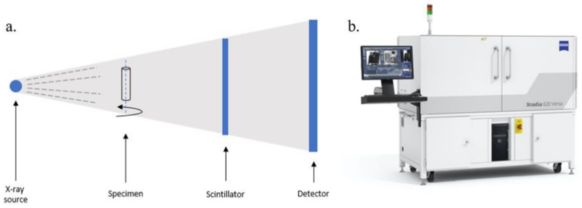

Figure 1. (a) Schematic of experimental set up for X-ray µ-CT imaging; (b) X-Radia-Zeiss equipment at UBC used to acquire µ-CT images of the soil samples.

2.2. Materials tested and specimen preparation

This research was undertaken using a silt-size granular material, a commercially available standard-sized silica particles, or silica dioxide, particles manufactured by SiliCycle, Quebec, Canada. As certified by SiliCycle, the shape of the grains is irregular; the particle sizes range from 40 µm to 63 µm.

Grain size distribution testing were performed on pre-calibrated silica particles using mechanical sieving as well as laser diffraction analysis. The specific gravity of the material is 2.02. Imaging of a randomly chosen set of particles of this material using a scanning electron microscope (SEM) revealed that the particles are mostly irregular (with some particles platy in shape) as seen in Fig. 2.

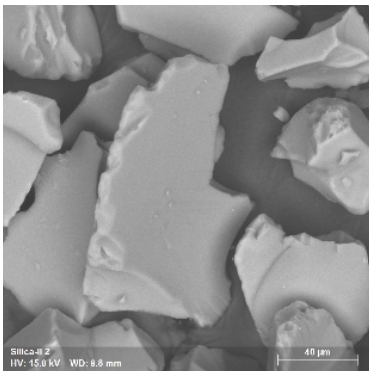

Figure 2. SEM image of silica pre-calibrated particles

Previous studies at UBC (Wesolowski 2020) while considering X-ray µ-CT scanning resolution requirements, it was determined that ~5-cm high specimens encased in thin-plastic tubes having a nominal diameter and wall thickness of 5 mm and 0.14 mm, respectively, were suitable for imaging silt-sized material. In cases where consolidated specimens were required (say, to obtain certain target void ratios), relatively larger specimens were initially prepared by placing reconstituted silty material in a polished-metallic ring (7.6 cm diameter and 11.5 cm in height) and then consolidating the material to the desired stress level. The required specimens (using the above mentioned thin-plastic tubes) for X-ray µ-CT scanning were obtained by "subsampling" from the above consolidated specimen - after trimming the top and bottom portions that are expected to be affected by the end effects. It is to be noted that the 11.5-cm high consolidation ring, taller than the standard 2-cm oedometer size, allowed accommodating significant vertical strains that are expected during the slurry consolidation process as well as preparing sufficiently tall (>5-cm height) subsamples as mentioned above.

3. Image processing and analysis

A given X-ray µ-CT scan, following a reconstruction process, would produce a voxel-based, greyscale 3D image volume that would serve as input for further image processing and analysis. Each individual voxel stores a grey level that is produced from the scanning process. As described in (Valverde & Wijewickreme 2021b), the analysis of the greyscale 3D image broadly consists of two steps: image pre-processing and image segmentation, and these steps were performed using the commercially available Avizo 9.7 software (TFS 2019). This software has been used by various researchers to successfully study particulate geomaterials (Markussen et al. 2019; Fonseca 2011). Image processing and analysis was completed in accordance with already established workflows at UBC, and they broadly consisted of two phases. First, the images were filtered in order to reduce any inherent noise, and segmented to partition the individual grains; herein, the "watershed" algorithm was used to segment the particles. Second, quantitative measurements were obtained from the resulting image. The label analysis tool was used to retrieve the data required for establishing grain size distributions, particle shapes and orientations, and void ratios. More details on the image processing are giving in the results Section 5.1 of this paper.

4. Particle morphology and soil fabric parameters

4.1. Particle morphology

The particle morphology is a fundamental component to describe soil fabric as it strongly affects the mechanical properties and the failure mode of soils. Numerous studies have been performed in sands to relate the particle size distributions to different parameters as the void ratio (Miura et al. 1997; Cubrinovski and Ishihara 2002) and the angle of internal friction (Holtz and Kovacs 1981).

One of the most fundamental ways to characterize soils, is by their particle size. The well-known particle size distribution (PSD) indicate the relative proportion of different particle sizes in a given soil. X-ray μ-CT image analysis can be performed to obtain precise 3D measurements of particle sizes (Mertens and Elsen 2006; Altuhafi and Coop 2011; Fonseca et al. 2012; Zhao et al., 2015).

Particle shape gives information about morphological and depositional history, as it reflects the weathering process as well as the initial particle deposition. There are numerous shape characteristics in the literature, some classic representations include using the Zingg's chart (Zingg 1935) to classify particles based on their shape as disk, equant, roller or bladed. This approach is based on elongation and flatness indexes. Similarly, other parameters typically used to characterize particle shape are roundness and sphericity. Powers (1953) proposed a quantitative roundness classification based on class intervals. These methodologies were used to characterize pre-calibrated silica particles.

4.2. Soil fabric parameters

The void ratio can be considered another most fundamental parameter in granular mechanics, and it is used to represent the density and heterogeneity of the soil matrix in a given specimen. It is defined as the ratio of the volume of voids (V_v) to volume of solids (V_s). The void ratio has been widely used to study soil behavior and much research has been conducted on the evolution of void ratio within a specimen under different loads (Oda 1972; Desrues et al. 1996; Fonseca et al. 2013a). Recently, imaging data processed by thresholding intensities has been increasingly used to obtain digital void ratios, and studies have been found to be in good agreement with laboratory obtained void ratios considering that the laboratory void ratios are global quantities that do not capture the local variations of density within the specimen (Fonseca et al. 2013; AlMabub & Haque 2016).

5. Preliminary results

5.1. Image processing and analysis

Fig. 3 presents the steps followed for image processing. The raw image of a silica specimen with particle sizes ranging 40-63μm is shown in Fig. 3a. It can be noted that due to the high resolution of the X-ray μ-CT image, inevitably some "salt and pepper" noise is present within the slice. To mitigate this and improve the image while conserving sharp edges, several digital filters were used including median filter, recursive exponential filter, and non-local means filter (Fig. 3b). With the purpose of isolating particles from their background (air and/or water), interactive thresholding technique was used for silica particles. Interactive thresholding is suitable for silica particles as all particles are composed of the same materials and therefore have identical density (Fig. 3c). This technique uses the histogram of a greyscale image and finds a single separation value. The separation value is selected by comparing different values on random slices and by visually selecting the value that delineated the particles closer to the original image. On the other hand, silt is a natural material composed of different minerals (i.e., various densities within a slice) and therefore using a single separation value would not be efficient in this step. Instead, adaptive thresholding is used for silt images where for each pixel a local threshold is computed from its local mean density. Remove small holes module is applied next to remove any voids within a particle (Fig. 3d). To remove the contacts between particles, a separate objects module is used, and then, each grain is labelled with a unique index (Fig.3e). Finally, the labelled image is trimmed all around the boarder to remove any artificial particles/artifacts created in the boundary during the analysis phase. The label analysis option gives individual particle data (i.e., length, width, breath, thickness, volume, orientation, etc.). This information is then exported, and in the present research, an in-house developed MATLAB code was used to obtain the different parameters.

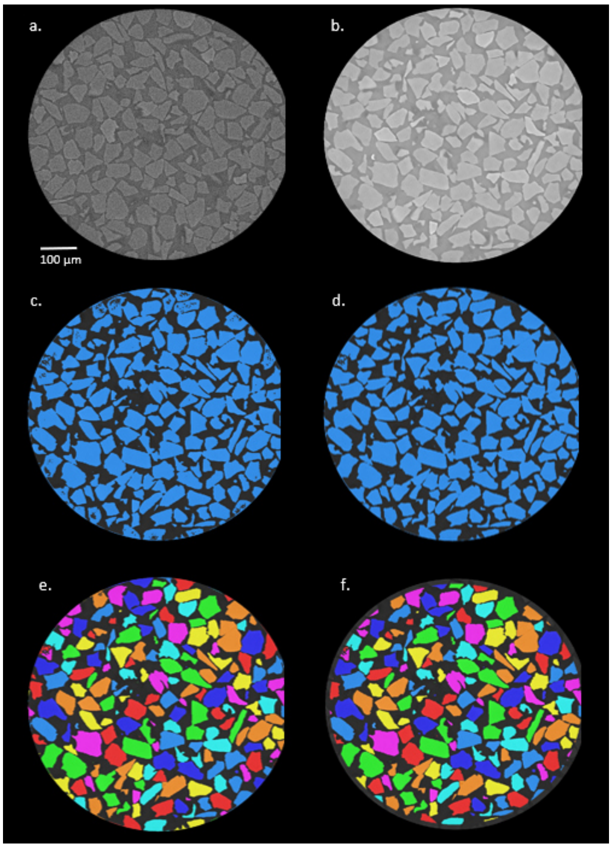

Figure 3. Image processing steps shown on a single slice. (a) acquired raw image; (b) after filtering to remove noise and sharpen the edges; (c) interactive thresholding to separate the particles; (d) filling of small holes to fill the voids in the soil particles; (e) labeling to give individual identification labels to each particle; and (f) final image, once the borders are trimmed to remove any artificial particles or artifacts.

5.2. Particle morphology

Particle size

The PSD curves obtained from laboratory mechanical sieving for the coarse-range (40 – 63 µm ranges) irregular pre-calibrated silica grains is presented in Fig. 4 for comparison with the counterpart curves obtained for the same material from digital data analysis. In addition to the data from digital processing, the PSDs generated from laser diffraction analysis and hydrometer analysis for the respective materials are overlain in the same figure. A general range of particle sizes between 40 – 63 µm is also marked on the same figure using shaded region. There seems to be good agreement between the mechanical sieving, laser diffraction and the digitally obtained PSDs for these coarser particle sizes. The results from hydrometer lead to curves that depict more fine-grained content compared to those from other methods. It is acknowledged that some of the differences may partly be attributed to experimental errors that are potentially inherent in traditional methods such as hydrometer analysis, mechanical sieving, and laser diffraction. Moreover, it is important to note that since mechanical laboratory testing gives very gross distributions, some adjustments may be required to match these results with advanced image analysis measurements (Hasan and Alshibli, 2010). In an overall sense, the observed mutual agreement for coarser standard-sized particles supports the suitability of the segmentation process for using in the coarser range of Fraser River delta silt.

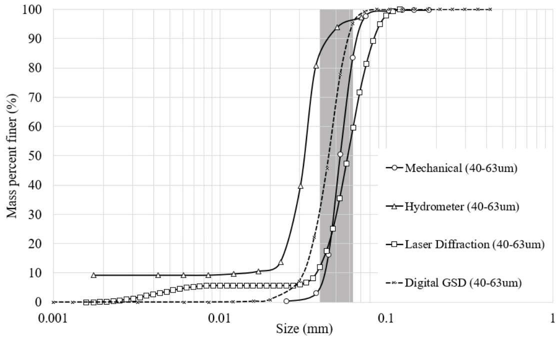

Figure 4. Digital and laboratory PSDs for silica material.

Particle shape

For categorizing particle shape characteristics, long, intermediate, and short axis lengths obtained from µ-CT imaging were classified according to Zingg's chart as shown in Fig. 5, and nearly all particles fell within the equant and roller shape index classification.

Other parameters typically used to characterize particle shape are roundness and sphericity. The roundness was calculated according to the criteria proposed by Hayakawa and Oguchi (2005), and all particles fell within the "very angular" classification as per Power (1953) class intervals. An example of the silica material comparing roundness to sphericity is shown in Fig. 6.

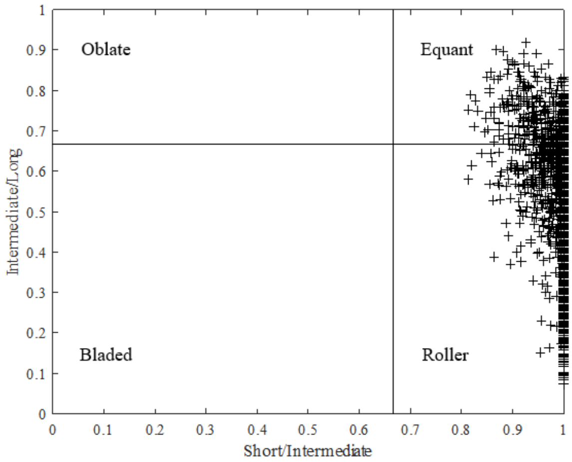

Figure 5. Zingg's particle shape classification for tested silica material.

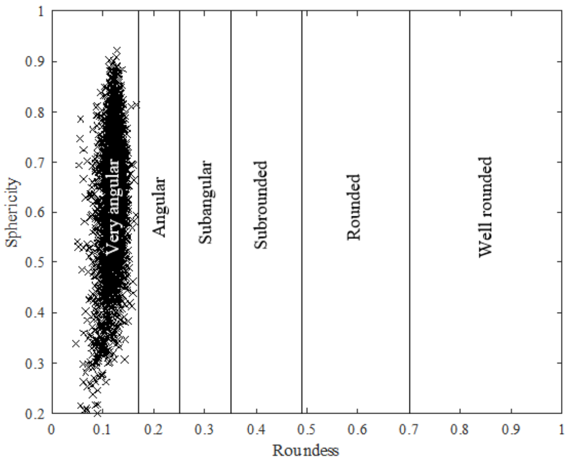

Figure 6. Roundness vs sphericity of tested silica grains as per Power (1953) roundness classification.

5.3. Preliminary fabric scalar parameters

The global void ratio was calculated from the processed images, where the solid phase is represented by the volume of the particles, and the voids phase is obtained by subtracting the known sample total volume from the obtained "solids volume". To obtain the solids volume, the sample must be binarized using an interactive thresholding which is highly subjective, and therefore, the approach would pose difficulties in obtaining accurate and repeatable void ratios.

Preliminary findings for quantitative results on void ratio were calculate for specimens consolidated to 100 kPa and 200 kPa effective stress levels. Four different silica specimens were consolidated to 100 kPa and the void ratios varied from 0.70 to 0.79, while one silica specimen was consolidated to 200 kPa and a void ratio of 0.67 was obtained. Moreover, void ratios were calculated for a natural Fraser River silt specimen consolidated to 200 kPa. A digital void ratio of 0.86 was obtained and the laboratory calculated void ratio was 0.87. There seems to be good agreement between the laboratory and digital void ratios obtained for the natural material. Moreover, it is important to note that despite the limited information on laboratory void ratios for the silica specimens, the digital void ratios portrayed the decrease in voids of the matrix with increasing effective consolidation stress.

6. Conclusions and future work

This paper presents some key experimental findings that demonstrate the ability of μ-CT imaging to study the particle fabric of silts and its associated particle parameters. In particular, particle morphology measurements were made to assess the particle shape of a pre-calibrated silica material which serves as baseline information for the current research on the fabric of silty soils. The established methodology for the processing of images was assessed using results from μ-CT imaging of pre-calibrated silica grains. Moreover, void ratio calculations were obtained using the processed X-ray μ-CT images at different consolidation pressures.

The importance of selecting an adequate/appropriate image analysis technique to process the μ-CT images was highlighted. It was illustrated that there is a need for different approaches when working with a uniform material (e.g., silica) compared to a natural material (e.g., Fraser River silt). The findings confirm the importance in using a systematic set of input parameters during the scanning process to obtain consistent results across different imaging made on similar material.

The relatively good agreement between the PSDs obtained from laboratory and digital imaging suggests the suitability of the image processing methods for identifying and segmenting silt matrices having particles between 40-63 μm. Additionally, silica particles were classified as equant and roller shape and fell into the very angular roundness classification.

Furthermore, both the laboratory and digital specimens resulted in very similar void ratios despite the complexities associated with the entailed calculations. Digital void ratios can be a useful tool to obtain local void ratios for fabric studies, which otherwise would be an impossible task from conventional approaches. However, it is recognized that this type of analysis requires high quality images to reduce the uncertainty in selecting a threshold to binarize the images.

In an overall sense, the initial results affirm the high capability of X-ray μ-CT for the visualization of fabric and microstructure of silts. Future work at UBC is intended to extrapolate these efforts and ultimately obtain fabric scalar and directional parameters for natural silt materials such as Fraser River silt.

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