

Particle Fabric Imaging for Understanding the Monotonic and Cyclic Shear Response of Silts

Dharma Wijewickreme¹ and Ana Valverde²

¹ Professor, University of British Columbia, Canada

² Ph.D. Candidate, University of British Columbia, Canada
dharmaw@civil.ubc.ca

Abstract. The current knowledge from experimental research has shown the significant effect of particle structure (fabric) on the monotonic and cyclic shear behavior of silts, in addition to the well understood influence of void ratio and effective confining stress. Advancing the knowledge on this matter requires systematic quantification of particle fabric in a given silt matrix in terms of individual particle parameters (e.g., dimensional sizes, volumes, shapes, orientations) as well as inter-particle contact arrangements. In the research work undertaken with this background, new methodologies were developed for X-ray micro-computed tomography (μ -CT) imaging of silts with specific attention paid to: sampling and preparing of silt specimens, scanning parameters to obtain the needed image resolutions, and digital processing of images to capture individual particle data. It is shown that μ -CT imaging is able to effectively image and capture 3-dimensional fabric of silt. The difference in the particle fabric between silt specimens reconstituted via gravity deposition and tamping is illustrated using the μ -CT images produced using standard-size silica particles. The fabric(s) developed from the imaging of natural low plastic silt is also presented, and the findings are shown to be well in accord with those inferred from the mechanical laboratory element testing of the same silt. The work contributes to the accounting for fabric in understanding the macroscopic shear behavior of natural silts.

Keywords: Soil fabric/microstructure, x-ray micro-computed tomography, low-plastic silts, liquefaction of soils.

1 Introduction

Liquefaction susceptibility of soils under seismic shaking has been studied globally for more than 50 years with much of the focus placed in the performance of saturated loose sands. Mainly as a result of the liquefaction-induced damage observed in the 1991 Chi-Chi, 1999 Kocaeli, and 2011 Christchurch earthquakes [1,2,3], seismic performance of silty soils have also been receiving increased attention. With this background, the study of low-plastic silty soils in the Fraser River Delta have been a topic of extensive research at the University of British Columbia (UBC), Vancouver, BC, Canada, for over 20 years. In this research, the shear behavior of relatively undisturbed and reconstituted slurry deposited silts has been investigated using a variety of methods

including laboratory direct simple shear (DSS) and triaxial testing. Effect of factors such as confining stress, void ratio, particle size, etc., on the monotonic and cyclic shear loading response of silts have been studied.

Soil fabric refers to the spatial arrangement of individual particles, particle groups, and pore spaces in soils [4]. Fabric focuses primarily on the characteristics of individual particles such as shape and size, and how this has led to their particulate arrangement [5,6]; the voids in this interpretation are those that are a direct result of the physical orientation and packing of the soil particles [7]. There are two main components to fabric: (a) particle's discrete orientation; and (b) its relative position with respect to adjacent particles [8]. There is evidence to indicate the significant effect of particle fabric and microstructure on the mechanical behavior of soils [9,10,11]. In particular, UBC research has shown that reconstituted Fraser River silt (despite having a higher density under essentially identical initial effective consolidation stress σ'_{v0}) consistently exhibits a weaker response compared to that observed from the undisturbed specimens of the same material. These significantly different behavioral displays by the same material suggest that it is important and timely to examine and systematically account for the effect of particle structure (soil fabric) on the silt response, in addition to the traditionally well studied effects of void ratio (e) and σ'_{v0} .

Research over many years has demonstrated that a given arrangement of particles in a granular mass undergo progressive changes when subjected to shearing stresses where the concentration of contact normal tends to increase in the major principal stress direction and particles align their longitudinal axis along the minor principal stress [12,13]. Past research in sands, comparing the behavior between soil specimens prepared using different reconstitution techniques, has shown that the macroscopic monotonic and cyclic behavior of soils is highly affected by the fabric and microstructure [9,14,15,16]. Moreover, studies have demonstrated that particle reorientation of sands occurs during consolidation [17]. Likewise, particle sphericity and aspect ratio have also known to cause varying changes in sample fabric and microstructure [18]. The effect of particle fabric on the coefficient of lateral earth pressure at rest (K_0) has also been demonstrated through compression testing of sands using an instrumented oedometer [19].

With this background, a research program using X-ray μ -CT imaging technology, has been undertaken at UBC to better comprehend the macro-level mechanical shear behavior observed from geotechnical element testing of natural silts. The work undertaken at UBC so far in visualizing silt fabric has resulted in promising observations thereby providing the impetus for undertaking further research on this subject [20,21,22,23]. In particular, technology and methodology for preparing silt specimens for X-ray μ -CT imaging as well as qualitative and quantitative post-processing of images have been developed. This paper presents these approaches and demonstrates their suitability for understanding the fabric of silt-size particle matrices. Images obtained from commercially available standard-size silica granules as well as natural silt originating from the Fraser River Delta of British Columbia, Canada, have been used for the intended purpose.

2 Background

2.1 Effect of fabric on the behavior of silts

Constant volume monotonic direct simple shear (DSS) testing at UBC has shown that reconstituted Fraser River Delta silt specimens prepared using slurry deposition method exhibit lower shear strength at all levels of confinement compared to those from undisturbed specimens. This behavior manifests despite reconstituted specimens having a denser arrangement compared to relatively undisturbed specimens. Moreover, the undisturbed specimens displayed a strain hardening response in contrast to the behavior observed for reconstituted specimens. The void ratio (e) and vertical effective stress (σ'_v) states after consolidation as well as after reaching relatively large shear strain levels ($\gamma \sim 15\%$) from these testing are plotted in Fig. 1. The e - σ'_v states of undisturbed Fraser River silt specimens, after-initial-consolidation and $\gamma \sim 15\%$, appear to follow straight lines. In a corresponding way, these semi-log-linear trends seem to also prevail for the after-initial-consolidation and $\gamma \sim 15\%$ states obtained for the reconstituted material. However, the lines for the reconstituted silt are at significantly different locations from that noted for the undisturbed silt; this is only explainable by the potential differences in the particle fabric and microstructure between the undisturbed and reconstituted soils.

Likewise, cyclic DSS testing has shown that reconstituted natural undisturbed silt generally exhibits a weaker response compared to that observed from the undisturbed specimens of the same material. Typical cyclic resistance ratio (CRR) observed between undisturbed specimens and reconstituted specimens in DSS loading is shown in Fig. 2. The reconstituted specimens displayed increased degree of stiffness degradation and strain accumulation potential compared to the relatively undisturbed specimen. It is evident that the decrease of void ratio and disturbance of natural fabric are two competing factors in governing the cyclic shear resistance of reconstituted material when compared to the cyclic shear resistance of undisturbed specimen. Clearly, these monotonic and cyclic DSS results highlighted the significant role played by the fabric in controlling the soil behavior and that it needs to be accounted in predicting the mechanical shear response of silts.

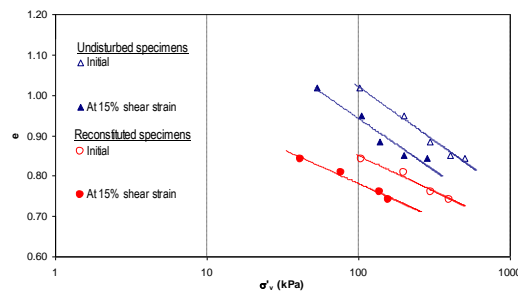


Fig. 1. e -log σ'_v relationships for undisturbed and reconstituted specimens of Fraser River silt immediately after initial consolidation compared with those after reaching 15% shear strain – extracted from [24].

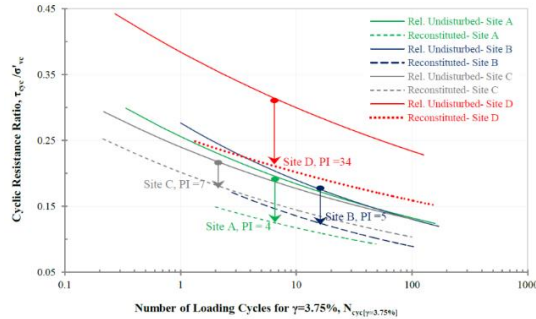


Fig. 2. Cyclic Resistance Ratio versus Number of loading cycles to reach $\gamma=3.75\%$ curves from constant-volume cyclic DSS tests indicating the reduction of cyclic shear resistance of reconstituted specimens with respect to relatively undisturbed specimens – results for soils from three sites from the Fraser River Delta as extracted from [10,25].

2.2 Evolution and quantification of fabric

The effects of soil fabric are difficult to observe and quantify in the laboratory. Several main techniques to obtain data for fabric quantification include: physical modeling using photoelasticity; imaging techniques using optical microscopy, such as scanning electron microscopy or X-ray computed tomography; numerical modeling using methods like discrete element methods (DEM). The noninvasive nature of imaging techniques represent a major advantage for conserving the soil fabric, and is increasingly being used to explore geomaterials. In this effort, methods such as scanning electron microscopy (SEM) and X-ray diffraction have led mostly to the retrieval of information on individual (or limited number of) particles; however, these methods have not been enabled to obtain a wholesome understanding of the particulate arrangements in a given soil matrix. On the other hand, by augmentation of ideas and applications emerging from the fields of medicine, computed tomography (CT) has been shown to be effective in visualizing the soil fabric. In spite of significant studies conducted using X-ray micro-computed tomography (μ -CT) with respect to sands and clays [26,27], only a very few studies have been conducted to image fabric and microstructure of silt size particles [11,28, 29]. As such, there is a need to further examine and systematically account for the particulate fabric in understanding the behavior of silts.

In recent years, the development of scanning technologies and high-performance computers has allowed large, three-dimensional (3D) datasets to be produced at micro- and nano-level resolutions [20,30,31,32]. These advancements and refinements now present an opportunity to extend μ -CT approaches to image and capture 3-dimensional fabric of silt specimens (i.e., particles sizes ranging between $2\ \mu\text{m}$ – $74\ \mu\text{m}$) and investigate their particle characteristics and influence on monotonic and cyclic shear behaviour. With this background, a comprehensive research program comprising the following multi-component objectives has been undertaken at UBC:

- a) Develop an appropriate soil sampling and preparation approaches for X-ray μ -CT imaging of silts

- b) Identify μ -CT devices and scanning parameters to obtain the needed resolutions for imaging of silts
- c) Conduct the needed digital processing of images to capture individual “particle data” (i.e., particle length, width, breath, thickness, volume, orientation, etc.) Calibrate/verify the developed methodologies and illustrate the capacity of μ -CT imaging to assess the fabrics derived from a given silt
- d) Examine the fabrics derived from the silt materials tested

This paper presents the outcomes arising from the above and demonstrates the suitability of μ -CT imaging to investigate the fabric of silt-size particle matrices and contribute to correlating that with the macroscopic behavior of natural silts. For completeness, some of the findings that have been reported previously by the authors are also briefly summarized and encompassed herein.

2.3 Test Materials, Preparation of Specimens, and Imaging Devices

Description of Material Used for Imaging

The research was undertaken using two silt-size (i.e., particle sizes ranging between 2 μm to 74 μm) granular materials. The properties and index parameters of the two silts are given in Table 1. One of the materials is a commercially available pre-calibrated, standard-size silica particles manufactured by Silicycle, Quebec, Canada; the standard silica material represents the coarser range of silt particles and two shapes. The use of these standard particle sizes provided an avenue to calibrate/verify the developed procedures and methodologies, conduct “bench mark” studies, and also extending the findings to study the full range of particle sizes present in natural silts. Relatively undisturbed samples of Fraser River low plastic silt retrieved from the Lower Mainland of British Columbia in Vancouver, Canada was chosen as the second test material representing natural silts.

Table 1. – Soil properties and index parameters of silts used in X-ray μ -CT imaging

Parameter	Standard-size silica particles		Fraser River silt
	Material type No.		
	I-40-63	S-45-63	
Specific gravity, Gs	2.02	1.89	2.75
Plasticity index, PI	NA	NA	7
Particle size range (μm)	40-63	45-63	2-74
Particle shape	Irregular	Spherical	Irregular

X-ray μ -CT scanning resolution and associated requirements limited the size of the sample able to be imaged. Based on the initial studies, it was determined that specimens of 5-mm diameter or less are required to meet the resolution requirements to characterize silty material using X-ray μ -CT imaging. This required containing silt specimens in tubes made of material having a significantly lower density compared to the tested soil grains (i.e., if the outer tubing material is very dense, the X-ray source energy will be highly absorbed, thus affecting the quality of imaging of the inner material). With this

in mind, metal containers were not considered. After investigating tubing made of several material types, including glass and polylactic acid (PLA) used as 3D printing material, it was found that thin-plastic tubing (having a nominal diameter $D = 5.0$ mm and $t \cong 0.14$ mm thickness with tube-diameter: particle-diameter ratio > 65) produced good imaging contrast with the inner silt specimen. In addition to securely holding the silt during imaging, the chosen plastic tube could be used to obtain relatively undisturbed sub-samples from larger laboratory samples of natural soils – i.e., similar to the approach in minimizing sample disturbance by using thin-walled tubes in the field.

Imaging Devices

In seeking suitable imaging equipment, μ -CT scanners from the following university research facilities were assessed to obtain non-destructive images of the UBC silt specimens: i) Composites Research Center at UBC Okanagan Campus (UBC-O); ii) Department of Civil Engineering at Monash University, Clayton Campus, Australia (Monash); and iii) Pulp and Paper Research Center (PPRC) at UBC main campus in Vancouver (UBC-V). Based on a detailed assessment [20,23], the ZEISS Xradia 520 Versa equipment (manufactured by Zeiss International, Oberkochen, Germany) available at the UBC-V PPRC proved to be the most suitable scanner at achieving the highest resolution, meaning the smallest voxel size, which was $0.869 \mu\text{m}$.

Image acquisition, processing and analysis.

The X-ray μ -CT scans produce 2D images of greyscale intensity, this parameter relates closely to the density of the material penetrated by the X-rays. Some thousands of consecutive 2D images are later stacked and reconstructed into a 3D image (Note: images were obtained considering the central 1-mm zone of the tube sample so that the imaged zone is well away from the tube walls). A given μ -CT scan output requires further processing to perform quantitative and qualitative image analysis with the process consisting of two steps: (i) image pre-processing; and (ii) image segmentation, and these steps were performed using Avizo 9.7 software [33]. This software has been used by various researchers to successfully study particulate geomaterials [34,35].

Reconstructed images from the scanning process were first filtered to improve the inherent noise from scanning and rectify artifacts. A given specimen should always be scanned at the highest resolution available for image sharpness; however, higher resolutions would introduce undesirably extra-noise in the resulting grayscale image [36]. In the approach developed herein at UBC, three different filters were applied: (i) 3D Median filter (MF); (ii) Recursive Exponential filter (REF); and (iii) Non-local means filter (NLMF). Typical outcomes from filtering during image-processing are given in Fig. 3. The MF is a low-pass filter that reduces the contrast and softens the edges in the image - reducing the “salt and pepper” noise induced by the scanner. The REF was used to smoothen the image. The NLMF enhanced the contrast and softened the image while preserving the edges of the particles.

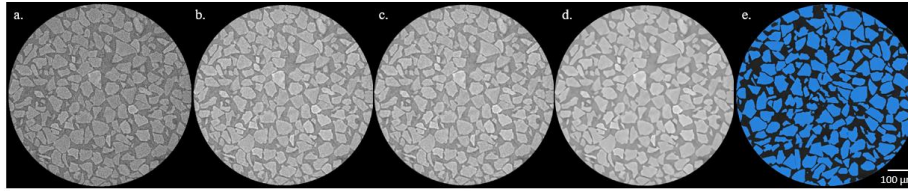


Fig. 3. Application of filters and thresholded μ -CT images: (a) raw image; (b) median filtered; (c) recursive exponential filtered; and (d) non-local means filtered; (e) final thresholded image.

Image segmentation consists of the application of a sequence of procedures to separate the in-contact solid particles from each other, and the solid particles from the void spaces. The first step to segment particles from the surrounding medium in a filtered image is typically conducted using a “thresholding” method that will produce a binary image that represents particles and its surrounding medium (usually air or water). The thresholding method by [37] is commonly used due to its simplicity and relatively fast application, and it has been widely used in sands [38] and incorporated in the Avizo software. Typical cross-sectional binary representation outcome of a thresholded image from Avizo software is illustrated in Fig. 3e.

Once data binarization is completed by thresholding methods, a segmentation algorithm separates the particles. A common procedure is to use a distance map transform and a watershed algorithm [39] that simulates water being poured over a landscape with peaks and valleys [13,38]. Finally, the particles are individually labeled in order to extract particle data, and a quantitative label analysis is required at this stage. Commercially available software is usually capable of extracting information related to particle data. These values constitute the basis for deriving grain size distributions, rose diagrams, etc.

Fabric quantification approaches

The data obtained with respect to grain orientation and size can be used to quantify fabric by scalar or directional parameters. Scalar measurements include the traditional void ratio approach, while directional parameters depend on the particle orientation along the long axis or contact distributions. In a 3D study, the directionality of the long axis of a given particle (particle orientation) can be described by angles denoted by θ and ϕ with respect to a radial coordinate system; where θ = the direction of long axis on a horizontal plane and ϕ = direction of the long axis with respect to the vertical. Such particle orientation “big-data” can be expressed by statistical representations like rose diagrams – i.e., angular histogram plots which displays directional data and frequency for a determined feature – which has been used herein to demonstrate the efficacy of the μ -CT scanning.

3 Findings from Standard-size Silica Matrices

The outcomes from investigations on standard-size silica particle matrices provided a way to calibrate/verify the suitability of μ -CT imaging technology to assess the fabric of silts and contribute to understanding the fabric of silt matrices as presented below.

3.1 Observations from Visual Inspection of Images

Fig. 4(a) and (c) present a section through the raw imaging data obtained from irregular-shaped, standard-sized (40 and 63 μm size range), dry and saturated silica specimens. This greyscale intensity plots reflect the density detected by the imaging device on the plane of the section, and these values form the key input data for the image processing. Visual inspection suggests that the device resolution seem to have been sufficient to capture the full range of particle sizes above 40 μm as well as to recognize their irregular shapes. Fig. 4(b) and (d) show the processed image, using Avizo software, with several filters to improve the image quality and segmentation algorithms to separate the particles, and obtain the required metrics. Again, it is notable that the segmentation algorithms have been able to identify/separate most particles in the image in spite of the limitations in digital image processing.

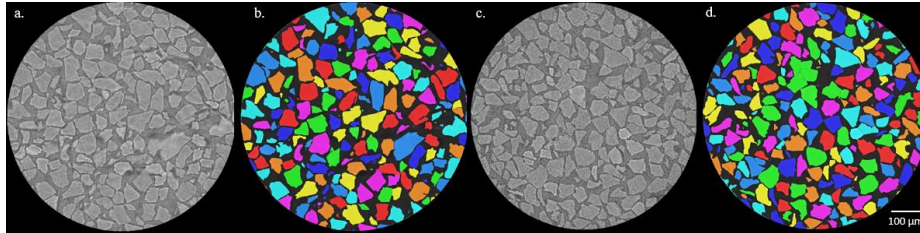


Fig. 4. Raw and processed tomography images for standard-size silica, respectively: (a) and (b) dry material; (c) and (d) saturated material.

3.2 Observations on Particle Shapes and Stratifications

A dry specimen of soil containing spherical-shaped silica zone (45 and 63 μm size range) overlying irregular-shaped silica layer (40 and 63 μm size range) was imaged. Fig. 5(a) and 5(b) present a segmented section through the spherical and irregular shaped zones, respectively. Fig. 5(c) presents the 3D view showing the two layers. The figures clearly demonstrate the ability of μ -CT imaging to identify/distinguish particle shapes as well as stratification/layering found in matrices of silt size particles.

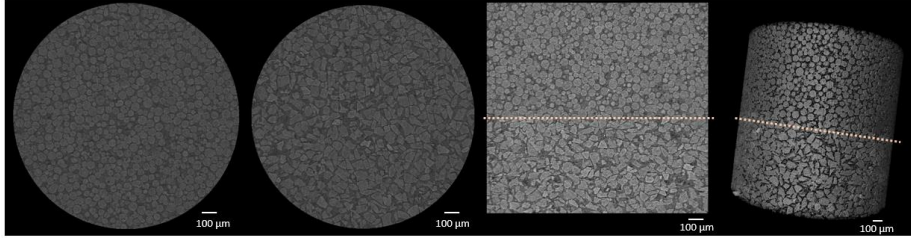


Fig. 5. Images from a subsample with two different shaped silica particles. (a) Cross-section through a spherical shaped silica zone; (b) Cross-section through an irregular-shaped silica zone; and (c) vertical section showing the layering; (d) 3D view showing the layering.

3.3 Observations on Particle size distributions (PSDs)

The PSDs in particle assemblies form a vital component in accounting for the soil fabric. Traditionally, the PSDs are obtained by laboratory mechanical sieving and hydrometer testing as per ASTM standards [40,41], respectively. The digital PSDs obtained from μ -CT imaging of the standard-sized silica grains were compared with those from mechanical sieving, laser diffraction analysis, as well as information available from the silica manufacturer. The details related to this work are described in detail in the companion paper in this conference by the authors [42]; as such, only the key findings are highlighted herein for brevity.

The PSDs obtained from the digital data analysis for both spherical and irregular standard-size silica particles were found to be in very good agreement with the specifications provided by the material manufacturer, and there was good alignment between the digitally derived PSDs for the saturated and dry specimens [42]. This showed that the imaging process is not significantly affected by the presence of water in the silt specimens; this is an important finding that confirms the suitability of the method to study the particle fabric in both saturated and unsaturated materials. The digital PSDs were also found to be in general accord with those from laser diffraction and mechanical analysis. Any observed differences were considered reasonable considering the limitations and differences in the techniques used. Overall, the work demonstrated the suitability of the fine-grained commercial silica as a “bench mark” research material and the potential of μ -CT for imaging silt fabric.

3.4 Evaluation of Fabric in reconstituted specimens

As noted earlier, the effect of particle fabric on the mechanical performance has been well recognized through tests conducted on sands. In consideration of this, two specimens of standard-sized (40 and 63 μm size range) dry silica particles were reconstituted using gravity deposition with one sample kept loose (as-deposited) and the other consolidated using vertical pressure applied using a plunger. The particle orientation data rose diagrams derived from the imaging of these specimens are presented in Fig. 6. The orientation of the principal axes of the particles in the consolidated specimen seem to align more parallel to the horizontal plane (Fig. 6b) than those of the particles in the

relatively loosely deposited specimen (Fig. 6a). The results are in line with the expected possibility that the compressive stresses applied on the gravity deposited specimens would have made the longitudinal axes of the particles to assume a position relatively closer to the horizontal. Again, the findings demonstrate the ability of μ -CT imaging method to capture the particle fabric in silts.

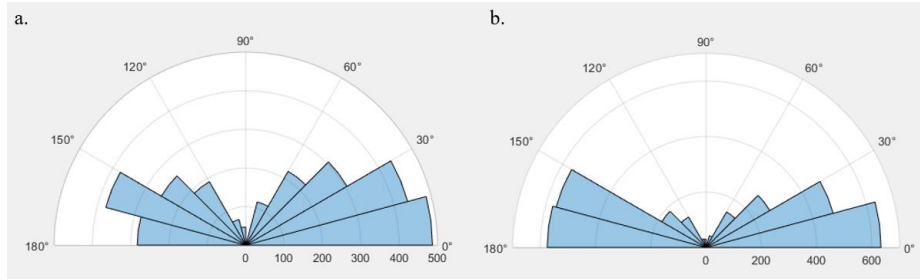


Fig. 6. Rose diagrams of particle principal axis orientation for reconstituted gravity deposited silica: (a) loose specimen; (b) consolidated specimen.

4 Findings from μ -CT imaging of Fraser River Delta Silt

As noted earlier, 5-mm thin-walled plastic tubes sub-sampled from larger “parent” samples were required to investigate the fabric of natural silt. With this in mind, a “parent” sample was generated by one-dimensionally consolidating a reconstituted Fraser River silt by a slurry deposition to $\sigma'_{vc} = 200$ kPa in a 76-mm diameter oedometer. Three sub-samples for μ -CT imaging were obtained from the parent specimen [23].

The raw and processed images for a specific slice in each sub-sample of Fraser River silt is presented in Fig. 7 (top and bottom figures, respectively) to illustrate typical images from μ -CT technology. The 3D images, visually do not show any layering or bedding; this confirms the non-segregation (uniformity) expected by the reconstituted specimens formed using slurry deposition. The digital grain size distribution of the silt using μ -CT data for the 3 different sub-samples are presented in Fig. 8. The excellent match of the grain size curves from these subsamples serves as evidence of very good uniformity within the parent sample from a grain size distribution point of view.

Particle orientation data derived from the 3 subsamples was used to create the rose diagrams shown in Fig. 9. Clearly, the principal axes of the particles in the subsamples seem to mainly align in directions close to the horizontal; this observation is much in accord with the previous observations related to particle orientations for gravity deposited specimens [8]. Furthermore, the similarity of the rose diagrams further supports the notion that the soil within the parent sample has a uniform constitution.

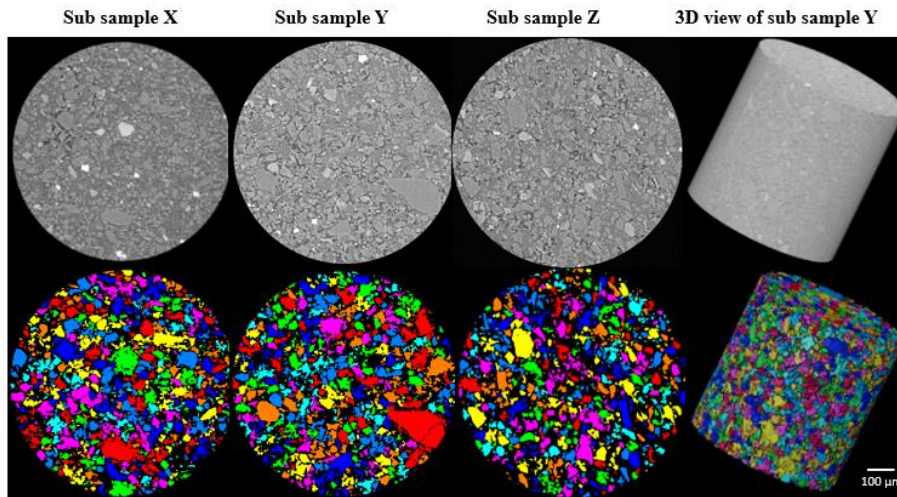


Fig. 7. Representative raw and processed images from three subsamples (X, Y, and Z) obtained from the same parent reconstituted specimen of Fraser River silt. (Note: Top Row – Raw grey-scale images; Bottom Row – Segmented images).

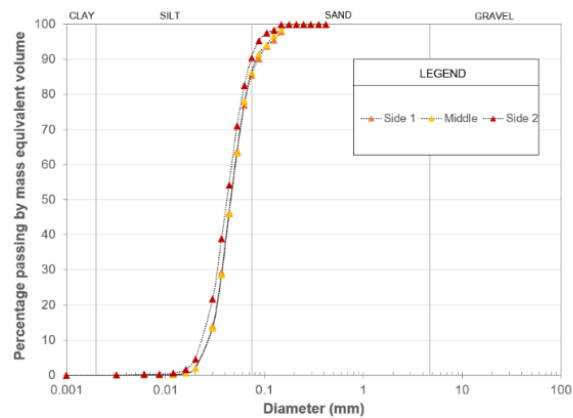


Fig. 8. Digital GSDs derived from the three subsamples (X, Y, and Z) obtained from the same parent reconstituted specimen of Fraser River silt.

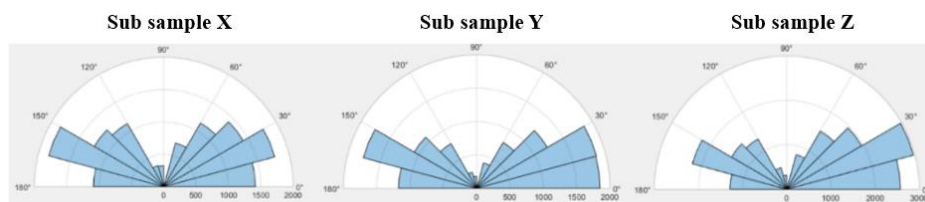


Fig. 9. Rose diagrams of particle principal axis orientation for the three subsamples (X, Y, and Z) obtained from the same parent reconstituted specimen of Fraser River silt.

5 Summary and Conclusions

Experimental evidence from laboratory shear testing clearly indicates that, in addition to the known effects of effective confining stress and void ratio, the particle fabric plays a critical role in governing the mechanical behavior of silts. Findings from the monotonic/cyclic shear testing research conducted at UBC on undisturbed and reconstituted natural low plastic silts, the void ratio and natural fabric have been realized as two important competing factors governing the shear resistance.

The research outcomes presented in this paper demonstrate the high potential of non-invasive X-ray μ -CT imaging technology to understand the soil fabric, and in turn support understanding the macro-level mechanical shear behavior of natural silts. Specially, the methodologies developed for: preparing silt specimens for X-ray μ -CT imaging as well as qualitative and quantitative post-processing of such images to obtain key “particle parameters” (i.e., such as particle dimensions, volume, and orientation of axes of grains) to support the expression of particle fabric are presented. Through examination of the orientation of the principal axes of particles found in specimens of standard-size silica grains, the difference in the fabric between loose and relatively dense silt is well illustrated. The validity of these observational trends is also extended to the fabric(s) derived from the imaging of natural low plastic silt originating from the Fraser River delta of British Columbia, Canada.

The methods developed so far have shown the excellent capability of X-ray μ -CT imaging to define the particle fabric for silt sizes above 40 μm . Additional work is underway to bring this resolution to image the particles below this size.

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