# TOWARDS UNDERSTANDING THE FABRIC AND MICROSTRUCTURE OF SILT – INITIAL FINDINGS OF SOIL FABRIC FROM X-RAY μ-CT

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## *Abstract*

The current understanding of the mechanical response of soils has been viewed to be governed by the density (void ratio) and effective confining stress, as determined by laboratory and field testing. Much research in liquefaction assessment of sandy soils have been conducted. However, the physical properties of finer grain particles, particularly of silts, offer additional challenges. Close to two decades of monotonic and cyclic shear studies performed at the University of British Columbia (UBC) in Vancouver, Canada, has shown that the behavior of natural silts is influenced by soil fabric and microstructure.

In some cases, laboratory tests clearly show that relatively undisturbed silt exhibit a stiffer stress-strain response compared to the behavior displayed by the specimens reconstituted from the same material – even though the former would possess a larger void ratio compared to the latter under the same effective confining stress. These observations validate the notion that soil fabric and microstructure must influence the behavior observed in laboratory element testing. Unfortunately, traditional invasive techniques have not been successful in providing adequate visualization of particle configuration.

To investigate the above, a research program has been undertaken at UBC to capture non-destructive three-dimensional images of Fraser River silt specimens using X-ray micro-computed tomography. The initial phase of this research has demonstrated the viability of this imaging technique for capturing fabric. This experimental study shows the fabric and microstructure of relatively undisturbed and reconstituted samples prepared by slurry deposition method and consolidated to three different stress levels. Preliminary observations on quantification of fabric and suggested improvements along the technology development are also presented.

*Keywords: soil fabric/microstructure; x-ray micro-computed tomography imaging; low-plastic silts; liquefaction of silts*

## 1. Introduction

The Pacific Coast of British Columbia, Canada is located in the “Pacific Ring of Fire”: the world’s most earthquake prone region where 90% of earthquakes occurs. Observations from past earthquakes (e.g. Turkey, Kocaeli 1999, and New Zealand, Christchurch 2010-2011) suggests that fine-grained silty soils with high levels of saturation are susceptible to earthquake-induced softening and strength reduction resulting in undesirable geotechnical hazards. Since the Metro Vancouver Region of British Columbia is located in a seismic region, significant research efforts have been undertaken at the University of British Columbia (UBC) to understand the effect of factors such as confining stress, void ratio, particle size, etc., on the monotonic and cyclic shear loading response of silts. However, only limited work has been undertaken to study the effects of soil fabric and microstructure on the mechanical behavior of silts [1].

Fabric refers to the arrangement of particles, particle groups and pore spaces in soils [2]. In sands, particles are large enough to behave as independent units. Past research in sands, comparing the behavior between relatively undisturbed versus reconstituted soils has shown that the macroscopic monotonic and cyclic behavior of soils is highly affected by the fabric and microstructure [3,4]. Moreover, when using different reconstitution techniques, different mechanical responses are observed [5,6]. Research demonstrates that a given arrangement of sand grains undergo progressive changes when subjected to shearing stresses where the concentration of contact normal tends to increase in the major principal stress direction and sand particles align their longitudinal axis along the minor principal stress [7]. Direct observations of this nature are very limited to non-existent in silts.

With this background, a laboratory program has been undertaken at the University of British Columbia to better understand the macro behavior of soils using microparticle physics, and the work constitutes part of a major study on the earthquake response of fine-grained soil deposits in British Columbia, Canada. The state of the art for studying the evolution of soil fabric is the use of non-destructive imaging techniques such as X-Ray micro computed tomography (micro CT). This imaging technique has been successfully used to visualize sand particles [8] and has been recently used in smaller particle size of 5 µm for visualizing hydrating cement paste particles [9]. However, research specifically in silts with particle size between 2 and 60 µm is limited. A first attempt to explore the feasibility of micro computed tomography in visualizing silts fabric at UBC has found to be promising [10]; and this paper presents some findings from further research conducted using this micro CT methodology. In particular, the soil material used, specimen preparation, and details related to the testing program are initially presented. This follows sections presenting image acquisition, processing and analysis, and in addition, conclusions and suggestions for future work.

## 2. Experimental program

### 2.1 Material description

Fraser River silt from the Lower Mainland of British Columbia in Vancouver, Canada was chosen as the geo-material for this research work. This silt originates from the upper Holocene sediments of the Fraser River delta alluvial system that was deposited since the retreat of the glaciers from the last glaciation (that subjected the area to high overburden pressures) some 11,000 years ago [11,12]. Relatively undisturbed samples used for this study were retrieved from a depth of 2.6 m to 4 m below the ground surface from a site located in the southern part of the City of Surrey, British Columbia. Geotechnical investigations conducted at the site included conventional mud rotary drilling and electrical seismic cone penetration testing with pore water pressure measurements; based on the available information, this material was assessed to be normally, or slightly overconsolidated. Mineralogical analyses carried out for this material revealed mainly the presence of quartz, plagioclase feldspar and illite-muscovite [10].



 

Table 1 – Soil properties and index parameters of Fraser River silt

| Parameter | Value(s) |
|---|---|
| Depth (m) | 2.6 – 4.0 |
| In-situ water content, WC (%) | 40 – 44 |
| Specific gravity, $G_s$ | 2.75 |
| Plasticity index, PI | 7 |
| Percent fines (%) | 15 |
| Unified soil classification | ML |
| In-situ overburden stress, $\sigma_v$' (kPa) | 30 – 42 |
| Normally or over consolidated | NC |
| Median particle diameter (μm) | 15 |

Relatively undisturbed specimens were extracted from the field tube samples using an upright extruder and trimmed to a smaller size in order to match with a polished-metallic ring used for consolidation testing. The material trimmings were saved and used to prepare reconstituted specimens for consolidation testing. Past research on sands has indicated that the method used for specimen reconstitution would impact the mechanical response observed in geotechnical element testing – later studies related this observation to the changes in particle fabric [13,14]. As such, the reconstituted specimens were prepared using the slurry deposition method; this method has been widely used by UBC researchers, and it is considered to accurately represent the natural deposition that occurs in a river environment [15,16,17].

## 2.2 Consolidation tests

A number of stress-controlled one-dimensional consolidation tests were conducted using the specimens reconstituted using the slurry consolidation method. The slurry was carefully placed in the polished-metallic ring (as described in the previous section and further detailed in the next paragraph), and the vertical load for consolidation was applied through a top cap and loading shaft as commonly done in these tests. The load was applied incrementally, and the slurry was allowed to consolidate resulting in a suitably firm specimen for subsampling as detailed below. The specimens were consolidated to three different vertical effective stress levels ($\sigma'_{vc}$) of 50 kPa, 100 kPa, and 200 kPa while ensuring the soil is fully saturated throughout the experiment.

Achieving high resolution in X-ray micro CT scans is limited by the specimen size. The conventional specimen size from a consolidation test (such as ~70 mm diameter) would be excessive to obtain a sufficient resolution from a micro CT scan to identify/image silt (i.e., "segment" particle sizes between 2 and 60 μm). As such, it was assessed that specimens of 5-mm diameter or less are required to meet the resolution requirements to characterize Fraser River silty material. Therefore, obtaining sub-samples from the already consolidated samples was required to arrive at specimens for the X-ray micro-computed tomography scans. The typical height of specimens arising from the polished-metallic rings used in conventional consolidation testing (~2 cm) was identified as a limitation, particularly considering that the zones at the top and bottom of the specimen are expected be disturbed due to the end effects. In order to overcome this drawback, a polished-metallic ring [10] with a height of ~11.5 cm (significantly taller than 2 cm) was specially fabricated to carry out the consolidation tests and extract representative sub-samples for X-ray micro CT scanning. Subsampling was conducted using a plastic straw; the feasibility of this technique for obtaining sub-samples for X-ray micro CT imaging was already shown in [10], and this information is not repeated for brevity.



 

## 2.3 Image acquisition, processing and analysis

High resolution non-destructive images were collected using micro CT scanners from 3 different university research facilities: i) Composites Research Center at UBC Okanagan Campus (UBC-O), ii) Department Civil Engineering at Monash University, Clayton Campus, Australia (Monash); and iii) Pulp and Paper Research Center at UBC main campus in Vancouver (UBC-V). The ZEISS Xradia MicroXCT 400 tomography equipment (available at UBC-O), and ZEISS Xradia 520 Versa equipment available (at Monash and UBC-V) were employed for this work.

The micro CT scans essentially produce images that record the variation of X-ray attenuation within objects, which is a parameter that relates closely to the density of material penetrated by the X-ray. Since the steadiness of the specimen during the scan is another key to achieve high-resolution images, a specimen holder was specifically designed and fabricated to good secure of the subsample during the micro CT scan. There are a number of parameters that need to be controlled to achieve scans providing images with a satisfactory resolution (expressed in terms of voxel size, which is essentially the 3-dimensional equivalent to the pixel size which is used in pictures with respect to 2-dimensions). For example, the field of view (FoV) – which is one of the key parameters to obtain a minimum achievable voxel size for the images – are given below: i) FoV ~4500 μm results in 3.2 μm; ii) FoV ~3200 μm results in 3.38 μm; and iii) FoV ~800 μm results in 0.77 μm. The lowest resolution achieved (i.e., the voxel size was 0.77 μm) would be equivalent to about 5% of $d_{50}$ of the median particle diameter of the Fraser River silt (which is 15 μm as estimated from hydrometer tests) - a resolution of < 3.5 μm was considered reasonable for the initial examination of Fraser River silt.

The reconstruction and analysis of the digital 3D images yielded from the equipment was performed using the commercially available Avizo 9.7 software (by Thermo Fisher Scientific) [19]. Various researchers have successfully used Avizo software to study geomaterials [8,18]. Image processing and analysis was completed in accordance with already established guidelines at UBC [10], and they broadly consisted of two phases. First, the images were filtered 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 and rose diagrams (for distribution showing orientation of contact normal directions as indicated in the next section). The feasibility of this technique was calibrated using glass beads as may be observable from the companion paper at this conference [20].

## 2.4 Fabric quantification

The arrangement of particles, particle groups, and pore spaces in soils are defined as fabric [2]. 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 represents a major advantage for conserving the soil fabric, and is increasingly being used to explore geomaterials.

The obtained data 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. The orientation of grains can be described in terms of the orientation of the particle with respect to a reference axis as shown in Figure 1a. In a three-dimensional study, the orientation of the long axis of a given particle (particle orientation) is described by angles denoted by theta (θ) and phi (φ). Such, particle orientation data usually include a large dataset of vectors that can be expressed by statistical representations like rose diagrams (Figure 1.b). A rose diagram is a circular histogram plot which displays directional data and frequency for a determined feature.

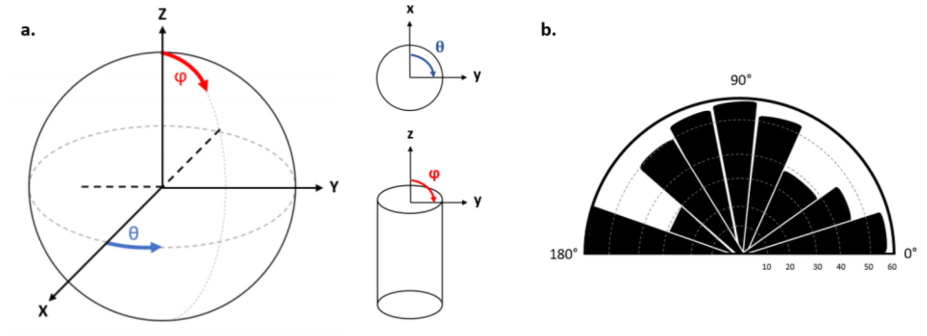


Figure 1 – (a) Three-dimensional orientation of a soil particle [10] and (b) rose diagram representation

## 4. Initial results and observations

Figures 2(a) through 2(c) present a section through the data obtained by X-ray computed tomography conducted on reconstituted specimens of Fraser River delta silt consolidated to a vertical effective stress of 100 kPa. The images are from different scanners and scanning parameters used in this study, and the difference in scanning parameters resulted in different field of views (FoVs) and resolution for the 3D datasets. The segmented image for the larger FoV (Figure 3b) was cropped to a smaller area because it was observed that the outer edge of the soil sample might be undergoing smearing effects (from the sub-sampling tube boundary) making it more difficult to distinguish multiple "grayscales". It can be noted that the use of a smaller FoV (Figure 3d) resulted in a significant improvement in the segmentation results.

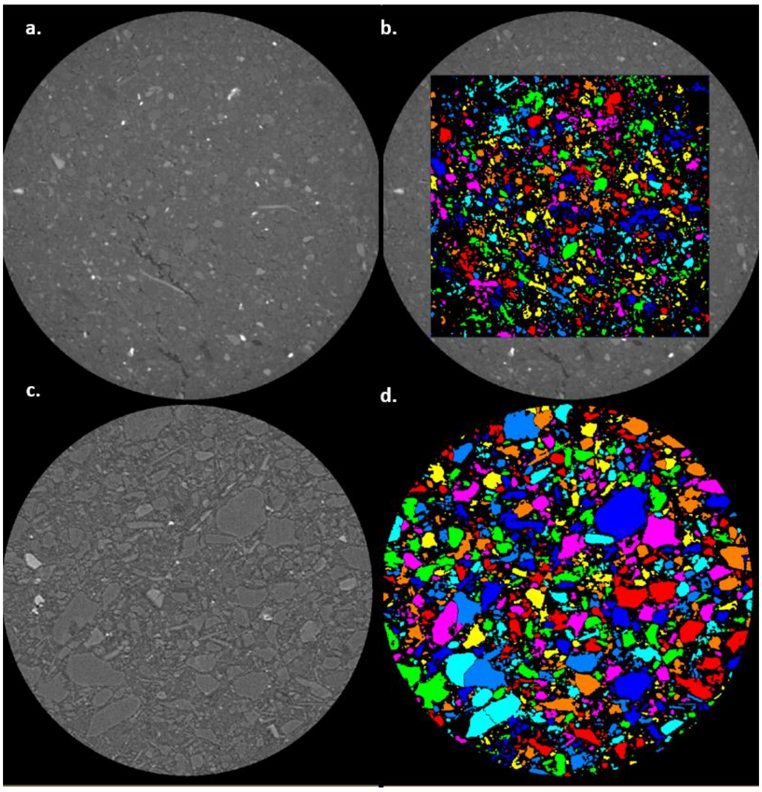


Figure 2 – (a) Section of tomography image of Fraser River silt with FoV: 3200 μm, (b) Section following segmentation for image a (resolution 3.2 μm), (c) Section of tomography image of Fraser River silt with FoV: 800 μm, (d) Section following segmentation for image c (resolution 0.77 μm).



 

Primary data on the orientation of the long axis of a given particle were obtained from the image processing (from micro CT equipment at the three research facilities as described earlier) and analysis were done with the purpose of plotting rose diagrams (Figure 3). It is to be noted that in Figure 3: The figures in Top Level, Middle Level, and Lower Level are for the data from the scanners at UBC-V, UBC-O, and Monash, respectively. As per the definitions in Figure 1, the value of $\phi$ equal to 0° and 180° represent when the orientation of the long axis of the grain is horizontal.

As may be noted from Figure 3(a) [Top Level], for the reconstituted specimen consolidated to $\sigma'_{vc}$ = 50 kPa, most of the particle axis orientations are aligned in a such way that the $\phi$ angles are between 15-30° and 150-180°. This suggests that the axes of most particles are oriented closer to the horizontal direction. It is of interest to note that this is in line with particle alignment orientations noted by [21] with respect to gravity deposited sands.

Comparison of Figure 3(a) [Top Level] with the Figures 3(b) and 3(c) [Top Level] suggests that no significant realignment of particles deemed to have occurred when $\sigma'_{vc}$ was increased from 50 kPa to 100 kPa, and then 100 kPa to 200 kPa, respectively. Since the consolidation was performed under one-dimensional conditions, as noted by previous researchers (e.g., [22]), in terms of stress path, this would essentially correspond to a case with a constant principal effective stress ratio (R = $\sigma'_1$ / $\sigma'_3$, where $\sigma'_1$ = major principal effective stress and $\sigma'_3$ = minor principal effective stress – i.e., $K_0$ loading path. Previous findings of constant gradients observed in strain paths when soils are loaded along with respect to constant R paths in element tests [23,24] have indirectly suggested that the fabric changes would be limited when a soil matrix is loaded along constant R paths. It appears that the above interpretation of no significant realignment of particles when $\sigma'_{vc}$ was increased from 50 kPa through 200 kPa from micro CT scanning seems to be in accord with that noted from geotechnical element (mechanical) testing.

Further examination will show that the above observations made with respect to the data from the scanner at UBC-V (i.e., Figure 3(a) through 3(c) [Top Level]) are qualitatively similar to those obtained from the other scanners at UBC-O and Monash (see Figure 3 Middle Level and Lower Level, respectively). In essence, the tendency of the particles to align towards the horizontal plane remained constant although the actual frequency of particles aligning towards different angles varied between scanners.


 

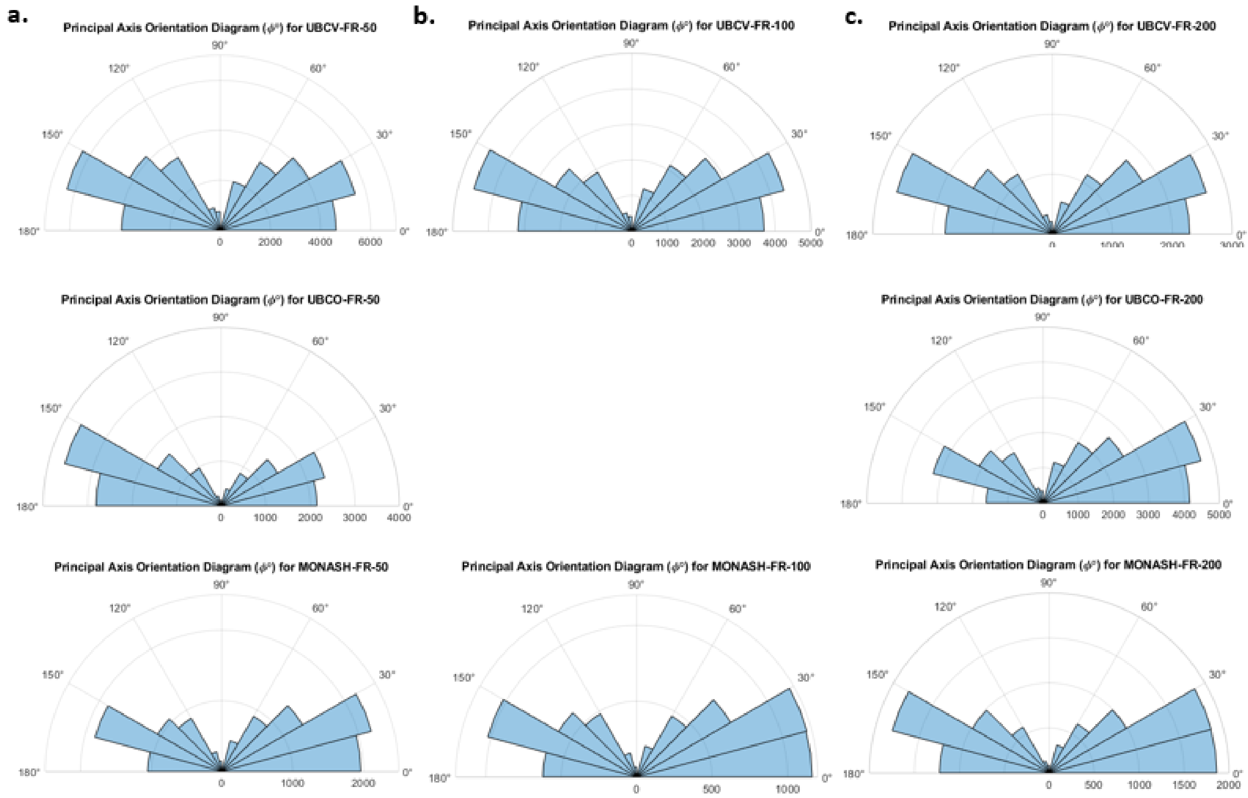


Figure 3 – Rose diagrams of particle principal axis orientation for reconstituted specimens at consolidation stress states of (a) 50 kPa, (b) 100 kPa and (c) 200 kPa using different X-ray micro computed tomography scanners. (Note: Top Level – Figures are from UBC-V scanner; Middle Level – Figures are from UBC-O scanner; Lower Level - Figures are from Monash scanner).

## 5. Conclusions and Future work

This paper presented some initial observations demonstrating the ability of micro CT imaging to study the particle fabric of silts. In particular, image analysis-based measurements were made to quantify how the particle fabric of Fraser River silt evolves when reconstituted specimens of the material one-dimensionally consolidated to increasing vertical effective stress levels. Initial findings show that the long axis of the particles of these reconstituted silt specimens consolidated to $\sigma'_{vc}$ of 50 kPa (prepared using slurry deposition) are predominantly oriented closer to horizontal plane. Moreover, no significant realignment of particles seemed to occur when $\sigma'_{vc}$ was increased from 50 kPa to 100 kPa under $K_0$ loading. It was of value to observe that these findings from micro CT scanning were in good accord with those noted previously by others from geotechnical element testing.

As expected, variability was found across the datasets, as all samples were obtained from different consolidation tests and using different scanners. However, the preliminary observations show that independently of the number of particles analyzed or the scanning parameters, comparable results are obtainable for assessing the principal axis orientation. The importance of selecting adequate equipment control parameters such as appropriate field of view to image the desired the particle size to be imaged was also highlighted. In an overall sense, these initial results signal the high capability of X-Ray micro CT for the visualization of fabric and microstructure of silts.

Future work at UBC is intended to refine scanning parameters to increase the image resolution (smaller voxel size) and achieve more accurate representation of particles. Improvement in density contrast is a priority to facilitate the segmentation of grain boundaries. Also, further work will explore the particle rearrangement that occur when specimens are subjected to other loading modes than compression, for example shearing, where notable rearrangements are expected to be observed. The final objective of this research is to relate microstructure to macroscopic behaviour of silts.

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