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TOWARDS UNDERSTANDING THE FABRIC AND MICROSTRUCTURE OF SILT – FEASIBILITY OF X-RAY μ-CT TO IMAGE SILT STRUCTURE

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Abstract

An extensive database generated from monotonic and cyclic shear element testing at the University of British Columbia (UBC), Vancouver, Canada, has shown that the soil fabric and microstructure has a significant influence on the behavior of natural silts. Despite tremendous potential to generate information on the stress-strain response of soils, laboratory element testing cannot provide direct evidence with respect to particle structure aspects. Visualization of particle arrangements through imaging techniques would be the key to advancing our understanding on this front.

With this background, a research program has been undertaken at UBC to capture three-dimensional images of Fraser River low-plastic silt using non-destructive X-ray micro-computed tomography. Current literature shows a wide variety of imaging conducted on coarse-grained, sandy soil specimens, as well as layering and fracture networks in clays and rocks. However, microparticle analysis of silt specimens has been rarely undertaken. Recent advances in technology and computing power have allowed for imaging smaller-grained specimens without compromising image resolution. In the initial work herein, the ideal specimen container for X-ray micro-computed tomographic imaging, as well as specimen moisture preservation involving wax sealing and sticky tack has been explored. Imaging has been performed at two generationally different scanners. The purpose of these multiple tests methods has been to assess the feasibility and image quality of the resulting scans for particle segmentation and three-dimensional image analysis. Preliminary image processing, particle segmentation, and quantitative analyses have been conducted. To verify the validity of this technique, results have been compared to laboratory-obtained grain size distribution curves. Upon initial visual inspection of the images, particle shape, size, and arrangement can clearly be seen. This is especially noted when observing the wall effects of the specimen sampling method. Early qualitative observations show that X-ray micro-computed tomography captures promising images for future analysis. This paper presents the initial findings from the early stages of this research program.

Keywords: soil fabric/microstructure; X-ray micro-computed tomography; low-plastic silts; specimen preservation; 3D image analysis.

1. Introduction

Several decades of data on liquefaction susceptibility of saturated loose sands has been gathered extensively from past earthquakes and research programs around the world. Recently, cases of problematic silty soils have arisen, such as in the 1991 Chi-Chi, 1999 Kocaeli, and 2011 Christchurch earthquakes [3, 4, 5], to name a few. In the seismically-active Lower Mainland region of British Columbia, a specific research focus has been placed on low-plastic silty soils. Fraser River Delta silts have been a topic of research at the University of British Columbia for over 18 years. In this work, the monotonic and cyclic 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. Several factors including effective confining stress, over-consolidation ratio, coarse-grained fraction, initial static shear bias, soil plasticity, and fabric and microstructure, have been shown to affect the behavior of silts [1].

A breadth of research has shown that fabric and microstructure have a marked effect on the macroscopic monotonic and cyclic behavior of soils [6, 7, 8, 9, 10]. This has been shown through differences in behavior between undisturbed versus reconstituted soils, as well as in variations of fabric due to the method of reconstitution during laboratory element testing. Research addressing this regime for silts has been limited [1]. Many researchers of sands have demonstrated that particle reorientation occurs during consolidation, notably that the long axis of the particle prefers to align itself more perpendicular to the applied load as the load increases [11]. Observations of particle sphericity and aspect ratio have also known to cause varying changes in sample fabric and microstructure [12]. The true microscopic fabric and structure of undisturbed silt specimens compared to slurry deposited silt specimens has never been explicitly explored.

The above has demonstrated that there is a lack of investigation in fabric and microstructure of low-plastic silt material. Due to its potential risk for liquefaction, it is imperative to understand how variations in laboratory practices on undisturbed and reconstituted specimens affect the soil's macro-behavior, and how this behavior is translatable to the in-situ field strength, particularly in the seismically-active region of British Columbia. Representative quantification of fabric and microstructure of fine-grained materials has been limited due to many constraints, including disturbance during sampling and specimen preparation. Optical microscopy and scanning electron microscope (SEM) technologies have been used in the past, however these methods are restricted to a two-dimensional plane of viewing [13]. Fabric and microstructure are inherently three-dimensional due to the complex shapes, arrangements, and orientations of particles and voids. X-ray micro-computed tomography (micro-CT) has been successfully used in the past for the non-destructive visualization of sand particles (> 75 μm diameter) and voids [14, 15, 16, 17], as well as a variety of other materials including concrete, rock, additive metals, and pulp.

Recent developments in X-ray micro-CT technology, accompanied by increased computing power capabilities, have shown that imaging of silt-sized particles ranging from 2 to 75 μm in diameter is now possible [2, 18]. Research specifically on silt for the application to geotechnical engineering is extremely limited to non-existent. Previous two-dimensional imaging techniques have failed to capture the undisturbed specimen fabric and microstructure which is contributing to the silt behavior, further reaffirming the need for X-ray micro-CT analysis.

An ongoing research program has begun at UBC with the broad objective of gaining insight into the influence of fabric and microstructure of silts on macroscopic monotonic and cyclic behavior. The main goal of this particular project was to develop a technology and methodology for preparing undisturbed and reconstitution specimens for X-ray micro-CT imaging, as well as identify reliable techniques for qualitative and quantitative post-processing of those images. This paper presents the initial images obtained from X-ray micro-CT imaging, along with their compatibility with laboratory findings.

2. Experimental Aspects

2.1 Material Tested and Specimen Preparation

A saturated silt material from one geographic location in the Fraser River Delta, Lower Mainland of British Columbia, Canada, was used in this research. This region has been subjected to high overburden pressures from glaciations over 10,000 years ago [19, 20], and more recently has been overlain with sediments from the Fraser River deltaic and alluvial systems [21]. The soil samples for this work were available from previous conventional mud-rotary drilling with fixed piston sampling using thin-walled, sharpened-edge, stainless steel tubes (76.2 cm in length, 7.32 cm in inner diameter). A summary of the soil properties and index parameters is given in Table 1.

Table 1 – Soil properties and index parameters of soil used in this study

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, σ_v' (kPa)	30 – 42
Normally or over consolidated	NC

Both relatively undisturbed and reconstituted samples were used for the purpose of assessing the particle fabric. The procedure for specimen preparation was near identical to that of a typical preparation procedure for monotonic and/or cyclic behavioral testing in order to maintain translatable results. Undisturbed samples were extruded using an upright hydraulic piston extruder and carefully trimmed using a soil lathe in a standard sharpened-edge testing ring 7.0 cm in diameter. Slurry deposition, as utilized by UBC researchers [9, 10, 22], was used as the method of reconstitution. Reconstituted specimens were consolidated in a conventional 1-D consolidation frame to vertical effective stresses of 50, 100, and 200 kPa.

Optimum specimen size for imaging was restricted to a maximum diameter of about 5.0 mm, due to physical constraints within the scanning machine (see next section for scanning equipment used) as well as recommendations for dataset size to perform an efficient analysis. Due to this optimum sample size for X-ray micro-CT applications, laboratory prepared specimens had to be "sub-sampled" or "cored".

Several smaller-diameter tubes were assessed for their ability to minimize disturbance during sub-sampling, while also being acceptable to use in the X-ray micro-CT scanning process [23]. In this regard, different material types, inner diameters, and wall thicknesses were assessed for sub-sampling tubes. A sample tube made of thin-plastic material (drinking straw), which had a D/t ratio of 37 (where D = Diameter of the tube; t = thickness of tube), was found to be the most conformant to the requirements, and this sampling tube was chosen for the preparation of specimens for X-ray micro-CT. Once the sub-samples were extracted from the specimens, they were sealed prior to shipping for scanning to prevent moisture loss. Conventional "sticky tack" (commonly used for mounting posters to walls) was shown to be superior regarding temporary moisture preservation of the sub-sampled soil specimens.

Various types of specimens were prepared using this sub-sampling method for a systematic imaging study to investigate the following topics with respect to X-ray micro-CT imaging feasibility of Fraser River Delta silt:

- Ability for the scanner to capture individual particles < 75 µm in diameter
- Calibration of post-processing procedure
- Comparison of image quality between soil specimens contained within different tube materials
- Observable differences between undisturbed and slurry reconstituted specimens
- Effect of resin impregnation on silt specimens

2.2 Non-Destructive X-ray micro-CT Imaging Equipment

The prepared sub-sampled specimens were sent to three different facilities with micro-CT scanning equipment, henceforth referred to as Scanner A, Scanner B, and Scanner C. Scanners A and B were ZEISS Xradia 520 Versa machines, while Scanner C was an Xradia 400 Versa. Both machine types were successful in obtaining images, however the Xradia 520 was advantageous in some respects. Firstly, the highest resolution with good image quality, or smallest voxel size, was achieved with Scanner B, an Xradia 520 model. This voxel size of 0.869 µm allowed for better visualization of the finer grained material in the silt specimen. The best possible resolution of the Xradia 400 was 3.16 µm. The images from Scanner C were 8-bit images, which yielded a range of 0 – 255 bits ($2^8 = 256$), while Scanners A and B yielded 16-bit images, resulting in 65,535 greyscale tonal variations in comparison. This significant increase in greyscale variation allowed for better contrast between minerals and soil constituents of similar densities. This distinction was essential for the filtering and particle segmentation image processing analysis.

3. Non-Destructive Imaging

Details related to the data processing from non-destructive imaging are presented in Wesolowski [23]. Only the salient aspects of this work are highlighted herein for brevity. Once the 3D datasets were acquired from the scanners, their quality was assessed in Avizo 9.7 software. The Median, Symmetric Nearest Neighbor (SNN), and Non-Local Means filters were compared for their ability to remove noise from the images while preserving edges of particles of interest. The Non-Local Means filter [24], while computational more complex, was found to be the most successful application in this regard.

One of the main requirements for analyzing particle fabric is to digitally segment the particles within the image in order to extract grain characteristics. In order to do this, firstly the appropriate greyscale level had to be chosen for each image to distinguish between solids (more white) and voids (more black) using interactive thresholding. The watershed segmentation algorithm was then applied to further segment particle boundaries. As shown in Fig. 1, the validity of this method was calibrated by imaging of specimens containing known-sized, 1-mm diameter glass beads [23]. This approach confirmed that the chosen filtering and particle segmentation methodology was reasonably successful in capturing individual particle diameter and volume, and image processing could proceed for other fabric and microstructure samples.

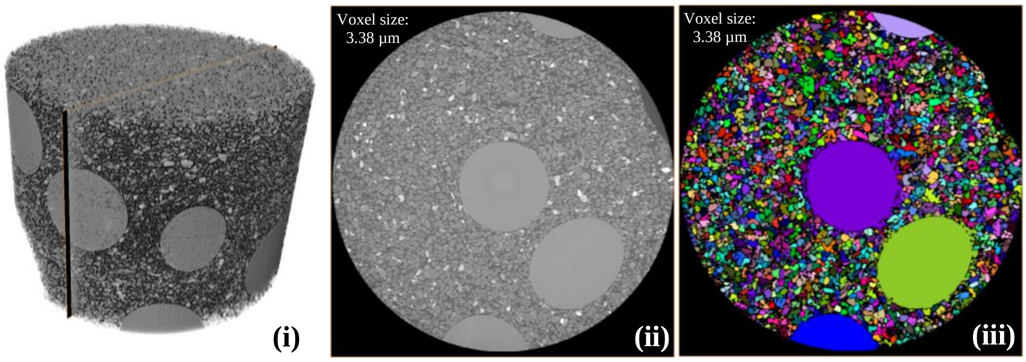

Fig. 1 – Glass bead calibration showing (i) 3D-rendering of dataset (ii) sample horizontal slice (iii) results of particle segmentation

4. Initial Results and Observations

4.1 Grain Size Distribution from Imaging

A digital grain size distribution curve was generated for each successful dataset. The minimum Feret diameter (d_{min}) was used in this regard as it is generally considered to be the best equivalent to laboratory sieving analysis [25]. Since grain size distribution is a cumulative distribution based on total mass, true 3D volume (V_{3D}) was considered equivalent to mass, assuming uniform specific gravity. The results of five digital grain size distributions are shown in Fig. 2, compared to hydrometer data obtained in this study as well as historical hydrometer data on Fraser River Delta silt.

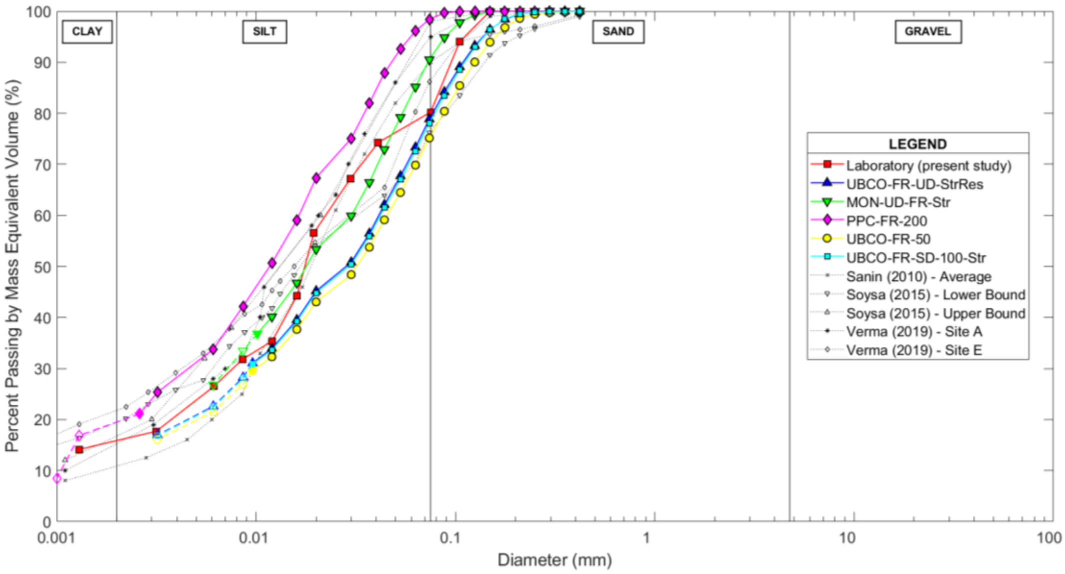

Fig. 2 – Comparative grain size distributions of various digital datasets

Most scanned images conformed to the laboratory-obtained dataset as well as previous datasets on Fraser River Delta silts by other researchers. Dashed lines in Fig. 2 represent the interpolated grain diameter, assuming a 3-voxel cut-off to represent whole particles. The highest resolution dataset (PPC-FR-200, resolution = 0.869 µm) appeared to over-estimate the fines content of the digital sample, while the lower quality images with higher noise (UBCO-FR-50, resolution = 3.2 µm) seemed to under-estimate the fines content. The most agreeable dataset was MON-FR-UD-Str (resolution = 3.38 µm), which was the exact material that, after being sub-sampled for undisturbed 3D imaging analysis, was dried, crushed, and used for the laboratory hydrometer analysis which is presented. There is inherent variability in where the specimen was sampled for each sub-specimen, therefore variability is expected. However, the digital grain size distribution curves still all fall within the silt range, following a similar trend to the laboratory and previous hydrometer test data.

4.2 Tube Wall Smearing Effects on Sub-Specimen Particle Structure

Fig. 3 presents an image that contained the full field of view of the specimen including the tube wall. The image shows smearing wall effects along the outer edge of the soil sample closest to the wall (about 1/10th of the diameter into the sample). It is quite visible that soil particles are arranged parallel to the wall and in a somewhat denser state. This denser state made it more difficult for the lower, 8-bit images to distinguish multiple greyscales within these regions, as the X-ray energy is first absorbed by the outer portion of the specimen. Nonetheless, these observations on wall effects can be translated to field sampling methods, showing how deep into the specimen diameter the sampling wall causes disturbance to the "natural" specimen.

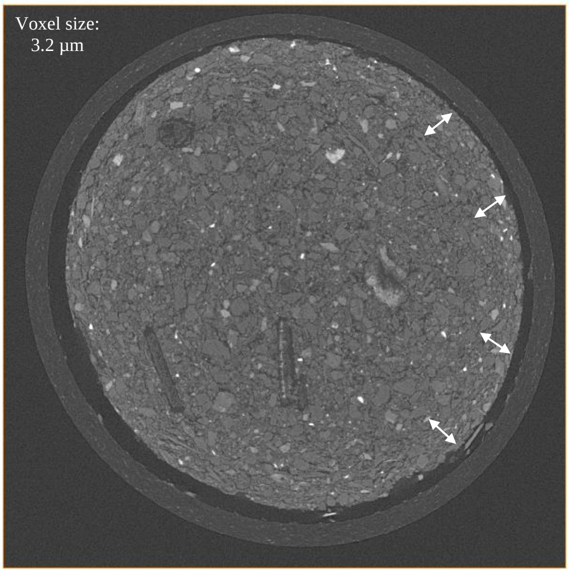

Fig. 3 – Sample slice showing full field of view and smearing effects from tube wall

4.3 Differences Between Undisturbed and Reconstituted Samples

The obtained datasets show that at the micro-scale, natural segregation or banding is evident in undisturbed specimens, but not in slurry reconstituted specimens (Fig. 4). This observation in natural soils could be in part due to seasonal variations, or more likely tidal conditions [20, 26]. For example, coarser sediment is deposited at riverbanks during the spring melt when the velocity is high, and finer material is deposited at calmer river flow points in the year such as summer. This relationship between velocity and particle size deposited is similarly applicable to tidal conditions. This banding is not observed in reconstituted specimens; their arrangement appears to be more random and well-graded throughout the height of the sample. This could be a possible reason for why void ratios for undisturbed specimens are typically higher than reconstituted specimens at the same stress state [9]. Since the fine-grained material is confined to these natural varves, infilling of void space does not occur as readily as when the specimen is intermixed in a slurry and then consolidated.

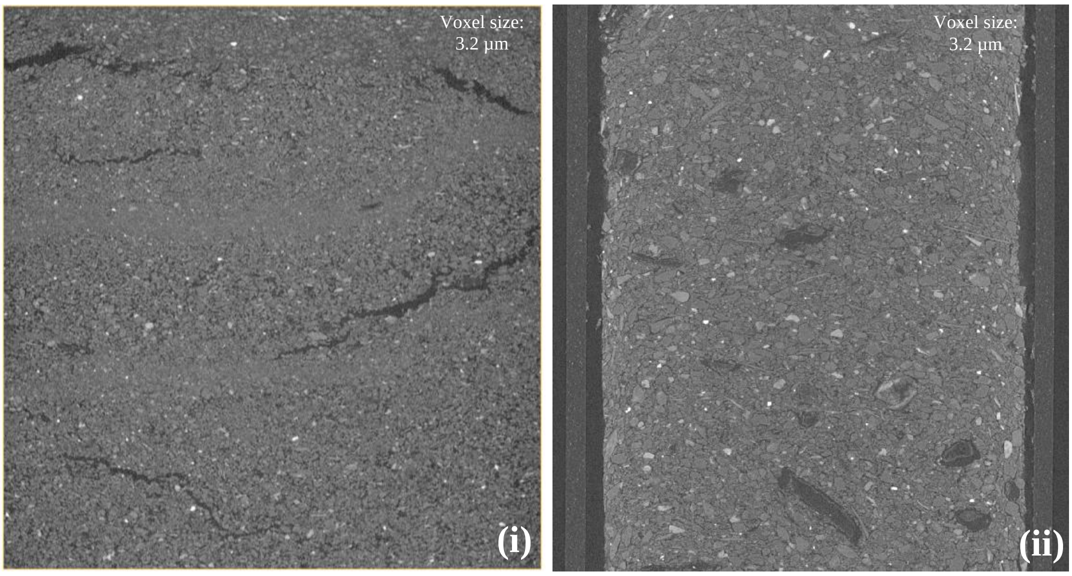

Fig. 4 – Sample vertical slices showing (i) preferential banding in undisturbed specimen and (ii) no banding in reconstituted specimen

With respect to the banding formation, it appears that larger-scale voids tend to occur in the coarse-grained banding areas. These voids, or "fissures", could be a result of drying of the specimen within the sub-sampled tube or the infilling of paraffin wax. These fissures may preferentially form in the coarse-grained areas due to larger void spaces being created, allowing for a path of lesser resistance for infilling fluids.

5. Conclusions

Preliminary findings in this research program have shown that X-ray micro-CT can be a viable option for the visualization of 3-D fabric and microstructure of silt material, particularly Fraser River Delta silt. A new sub-sampling technique had to be developed to prepare specimens to be compatible with scanner and dataset size restraints. A thin-plastic tube (drinking straw) was found to be the presently best option for sub-sampling laboratory prepared specimens. Future work will investigate other tube-material-geometry types that would allow obtaining specimens with minimal disturbance to the soil fabric while meeting required logistics and parameters for X-ray micro-CT scanning.

Verification of the X-ray micro-CT scanner's capability to produce high-quality images of individual particles was conducted using 1-mm diameter glass beads. The Non-Local Means filter reduced image noise while maintaining particle edges, and the water segmentation methodology yielded accurate segmentation of the glass beads. These steps were applied to datasets of Fraser River delta silt specimens of voxel sizes ranging from 0.869 μm to 3.38 μm. Both undisturbed and slurry reconstituted specimens were imaged. Initial quantitative results show closely matching grain size distribution curves for laboratory and digitally segmented datasets. Qualitative observations show that the wall effects resulting from tube sampling disturb the soil structure up to an annular zone involving $1/5^{th}$ of the total specimen diameter; in this zone, particles seem to reorient themselves parallel to the tube wall. X-ray micro-CT scanning was also successful in demonstrating marked differences in undisturbed versus slurry reconstituted specimens. Preferential micro-scale banding was noted in undisturbed specimens, while none was noted in reconstituted specimens. This initial work paves the way to use X-ray micro-CT scanning to investigate and characterize the particle fabric of silt, particularly with respect to identifying the effects of void ratio, confining stress levels, shearing, etc., on the mechanical behaviour of silts.

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