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Disturbance of sand samples obtained by piston samplers and ground freezing

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ABSTRACT

High quality sampling of sand and silty sands is extremely challenging. Undisturbed samples of sand can be obtained by means of very expensive and time-consuming techniques such as ground freezing. Given the high costs and expertise required to obtain undisturbed sand samples through ground freezing, piston sampling techniques are usually used in engineering practice. This paper summarises the experiences, technical difficulties, disturbance analyses and issues encountered during sand sampling at the Norwegian Research Site at Øysand using piston sampling and ground freezing technology. Two state-of-the-art piston samplers were used (NGI-Geonor composite piston sampler and Geonor K-200 thin-wall push piston sampler) along with the state-of-the-art Japanese gel push piston sampler. Ground freezing was successfully achieved also both on sands and silty sands at Øysand. Sample disturbance was assessed qualitatively and quantitatively through analysis of micro-computed tomography images. Results from these analyses provide an overview of the strengths and weaknesses of the three piston samplers in comparison with ground freezing, together with recommendations for sampling of sands using piston techniques.

Keywords: Undisturbed sand; push piston sampling; ground freezing; fabric.

1. Introduction

This research integrates with the Norwegian Geo-Tests Sites (NGTS) project (L'Heureux & Lunne, 2020) led by the Norwegian Geotechnical Institute (NGI). The NGTS infrastructure is a geotechnically well-documented arena for the entire geotechnical community for basic and applied research on soil testing and includes five geotechnical test sites: a silty sand at Øysand (Quinteros et al. 2019), a silt site at Halden (Blaker et al. 2019), a soft clay site at Onsøy (Gundersen et al. 2019a), a quick clay site at Tiller/Flotten, (L'Heureux et al. 2019) and a permafrost site in Longyearbyen, Svalbard (Gilbert et al. 2019).

Sand and silty sand deposits are common in many parts of the world, including rivers, offshore banks and deltaic areas, where many major cities are constructed. Saturated uncemented soils, such as sands, silty sands, gravels and other mixtures are extremely difficult to sample while ensuring that the *in situ* fabric remains intact. Where fabric is defined as the particle sizes, shapes and their distribution along with the arrangement of grains and their contacts (Mitchell & Soga, 2005). Because of the difficulties related to sandy soil sampling, these soils are commonly obtained (e.g. offshore) in a disturbed state and later reconstituted in the laboratory to target void ratios that are empirically derived from *in situ* tests such as the cone penetration test (CPT).

Allegedly, improved sampling techniques, e.g. block sampling (for cemented locked sands with fines above the ground water table), the Bishop sampler (Bishop, 1948) and the Gel-Push sampler (GPS after Mori & Sakai, 2016) are able to obtain undisturbed sandy soils. However, those sampling methods may cause either densification or loosening of sand samples depending on the sand's initial state, cementation, interlocking, or matric suction, and samples may not have sufficient high quality, for instance for determination of liquefaction (Broms, 1980). Moreover, disturbances during sample transportation, handling, extrusion, and specimen preparation may contribute to changing the initial sand fabric before a specimen is even tested in the laboratory.

The goal of this research was to investigate the effect of sampling disturbance from state-of-the-art push piston sampling techniques, including the GPS, and ground freezing at the Øysand site. Sample disturbance was assessed qualitatively through visual inspection, analysis of X-ray Micro-Computed Tomography (μCT) images and quantitatively using the recovery ratio achieved with each sampler. These analyses provide an overview of the strengths and weaknesses of three piston samplers and the ground freezing technique used for sampling Øysand soils.

2. Øysand research site

The Øysand site is located about 15 km southwest of Trondheim, Norway. The sands and silty sands deposits originate from the Gaula River, which flows into the Trondheimsfjord and borders the research site to the east. The deposit at the site consists of fluvial soil layers, underlain by deltaic and marine sediments. The deposits found at Øysand today were produced by glacial erosion of the bedrock and fluvial erosion of marine and glacial deposits in the catchment area. The major mineralogical components of the bedrock and glacial deposits are quartz, feldspars, illite and chlorite, with the latter making up the main proportion of the clay fraction.

Due to its geological history, the Øysand soil is layered with significant lateral variability. In general, the stratigraphy down to 20 m below ground surface can be divided into two main units: I) coarse to gravelly sand (fluvial deposit) from 0-10 m, and II) a lower unit consisting mostly of fine silty sand (deltaic soils) from 10-20 m. Unit II consists mostly of deltaic foreset beds dipping at an angle up to 20-25°. Figure 1 shows CPT results performed over the entire area of the Øysand site. The variability of the CPT data per depth is explained by the depositional history of the site.

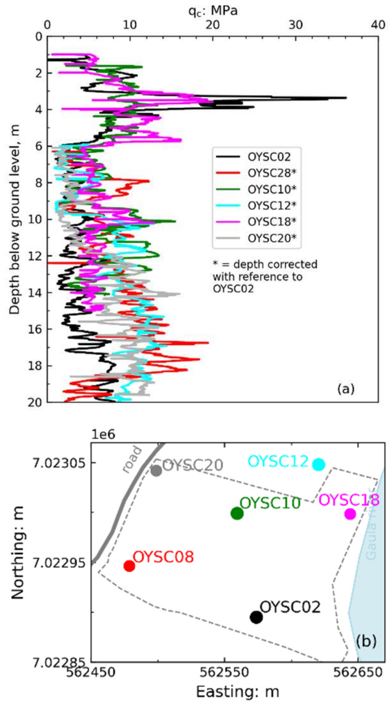

Figure 1. CPTU test around the Øysand research site: (a) q_c values versus depth, and (b) location of CPT tests.

Representative particle size distribution (PSD) curves of Øysand soil samples are presented in Figure 2. The fine to coarse sandy gravelly soil of Unit I from about 0 to 10 m depths is mostly classified as well-graded sand (SW) after ASTM D2487-17 (2017), while the sandy silty layers of soil from Unit II from about 10 to 20 m depths are classified as silty sand, non-plastic silt and poorly graded sand (SM, ML and SP respectively). The fines content (FC, particles <0.075 mm) ranges from 3% to 84%, depending on the soil layer of interest.

3. Sampling techniques used at Øysand

Sampling techniques used in this research included piston sampling and ground freezing. Due to the high soil variability at Øysand, few samples of the exact same soil were available. Due to the lack of a direct comparison between samples, this study focuses more on the experiences, technical difficulties, sample disturbance and issues encountered during sampling with the various samplers more than a one-to-one comparison between samplers.

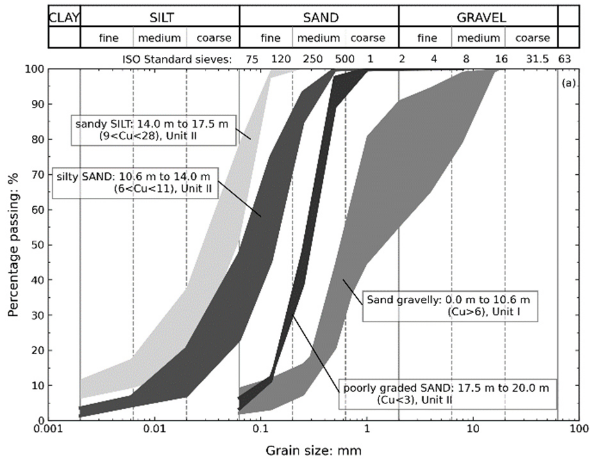

Figure 2. Typical grain size distributions of Øysand soils.

3.1. Piston samplers used at Øysand

Three different piston samplers were used to obtain sandy soil at the Øysand site. The state-of-the-practice pistons used were the (i) stationary NGI-Geonor composite piston sampler with liner and an internal diameter of 54 mm (PSØ54) and the (ii) Geonor K-200 thin-wall push piston sampler of 72 mm internal diameter (PSØ72), while the state-of-the-art sampler used was the (iii) Japanese gel push piston sampler with an internal diameter of 71.5 mm (GPSØ71). As explained below in more detail, and due to the difficulties faced while sampling gravelly sand pockets at Øysand, only very few samples were obtained with these samplers, especially when using the PSØ72 and the GPSØ71 piston samplers.

3.1.1. NGI-Geonor piston sampler (PSØ54)

The PSØ54 main components are shown in Figure 3a. The maximum sample length (L_{sl}) that can be obtained with this sampler is 725 mm. Hence the L_{sl} to internal diameter ratio is L_{sl}/D_i = 13.4. Detailed descriptions of the PSØ54 sampler are found in Vold (1956), Berre et al. (1969) and Andresen & Kolstad (1979). The PSØ54 has been allegedly used with success during the sand sampling campaign at Holmen in Drammen, Norway (Lunne et al., 2003). Based on that study, Geonor stated that 'excellent samples of loose to medium-dense sands' can be obtained if the borehole is filled with drill mud during sampling (see Geonor PSØ54 technical brochure, www.geonor.no). Filling the borehole with drill mud is done to stabilize the hole and to avoid decreasing the vertical effective stresses on the sample to zero. The area ratio (AR) of a sampler expresses the relationship between the volume of displaced versus sampled soils, while the external largest diameter to thickness ratio (B/t) controls overall distortion around the sampler. Due to poor sampler geometry (high AR = 45% and high B/t = 12), sample disturbance has been reported in previous studies even when sampling clay (Tanaka et al., 1996; Long, 2006; Lunne et al., 2006).

3.1.2. Geonor K-200 piston sampler (PSØ72)

The PSØ72 sampler can retrieve a sample with a maximum length of 820 mm, hence a L_{sl}/D_i ratio of 11.3. The PSØ72 is commonly used for sampling clay and has also been used to successfully recover silt at the NGTS Halden research site (Blaker 2020). The PSØ72 is basically an open cylinder with sharpened edges with no core catcher (Figure 3b). Its thin-walled steel cylinder edges allegedly reduce sample disturbance. Detailed descriptions of this sampler are provided by Berre et al. (1969). The PSØ72 has been reported to be able to obtain good quality samples, i.e., similar in quality as block samples in silt and inducing limited disturbance in clay (Carroll & Long, 2017; Clayton & Siddique, 1999). The AR = 11, while the B/t ratio = 39.

3.1.3. Japanese Gel push sampler (GPSØ71)

The Japanese Gel Push Sampler (GPSØ71) is a relatively new sampling technique developed by Kiso-Jiban Consultants in Japan for obtaining high quality sand samples at a reasonable cost. The name "Gel Push" derives from the required use of a viscous polymer gel, which acts as a lubricant, while sampling or extruding samples from the tube. Mori & Sakai (2016) reported a twenty-fold reduction in the thrust force needed to extrude a sample of the thin wall tube when the polymer gel was used. The gel also provides 'protection' to prevent sand from collapsing under low or no confining stresses. The polymer is not circulated through the piston, as is done with drilling fluid in other samplers, but it is rather pushed out of the sampler to minimize friction between the cutting shoe, the liner, and the soil being sampled. The main components of the GPSØ71 sampler are: (i) the stationary piston, (ii) the sampling outer tube and core liner tube, and (iii) the piston for activating the core catcher, see Figure 3c.

Figure 3. Piston samplers used: (a) Geonor-NGI PSØ54, (b) Geonor-NGI PSØ72 (www.geonor.no), and (c) Gel push sampler GPSØ71 (Kiso-Jiban, 2016).

The maximum sample length is 1 m, with an internal diameter of 71.5 mm, hence L_{sl}/D_i = 14. To avoid sample damage due to over-pressuring of the polymer gel, the recommended penetration rate is about 1 m/min. The polymer gel used with the GPSØ71 sampler is a non-Newtonian fluid, which has a very low viscosity when sheared, but that also provides normal stress confinement when in repose. The polymer is a partially hydrolysed polyacrylamide (PHP). The AR of this sampler is 69%, while B/t = 8.7. GPS samples obtained in other sands and silty sands were reported to be of high quality, so that the initial fabric of the soil was intact, see Taylor et al. (2012) and Stringer et al. (2015).

3.1.4. General observations during piston sampling

To avoid collapsing of the borehole in the gravelly layers, casing was installed between 0.5 m above the ground (protruding outwards) to 6 m depth below the ground surface. To stabilise the borehole and create a slight overpressure, the casing and borehole were filled with drilling mud (when using the PSØ54 and PSØ72 samplers) or with water (when using the GPSØ71). Sampling with alternating drilling was used to reach the desired sampling depth. Drilling was used to clean the boreholes, even though the samplers have a fixed piston system that does not allow undesired soil to enter the sampling tube while lowering down the tools. Nevertheless, borehole cleaning prior to sampling was deemed essential (after trial and errors) to avoid damaging the piston samplers' edges during sampling.

3.2. Ground freezing and sampling with Geofrost coring

Ground freezing is considered the most suitable stabilisation technique to obtain undisturbed samples of non-frost susceptible uncemented sands (Yoshimi et al., 1977; Sego et al., 1994; Robertson et al., 2000a; Ghionna et al., 2001), although the costs of such operations can be restrictively high. Ground freezing has been successfully used in Japan, Canada, USA and Italy. Liquid nitrogen (LN2), brine (calcium chloride, MgCL2), or ethanol mixed with ice are feasible cooling fluid options for freezing the ground (Stoss & Valk, 1979; Andersland & Ladanyi, 1994), and radial freezing has been reported to be more effective than vertical, because soil permeability is typically higher in the horizontal direction than in the vertical direction. To pursue ground freezing, the vertical effective stresses *in situ* must also be sufficiently high, and the fines content must be low enough, to avoid frost heave expansion.

Ground freezing for sampling at Øysand was carried out in Spring 2019 through a collaboration between NGI and Geofrost AS. Geofrost is Scandinavian company that specialises in ground freezing and assisted with all the technical and equipment requirements for freezing the ground, measuring the ground temperature, and coring the samples using Geofrost coring. Freezing was done around pre-installed piles to maximum depths of about 15.5 m in average. The equipment used was for freezing the ground was: (i) a diesel electricity generator, (ii) heat exchange unit, (iii) brine storage tank, (iv) circulation pumps, and (v) a pipe system for brine circulation. The freezing process consisted in circulating brine into a close system of freezing pipes that were installed inside some pre-installed piles. Brine was circulated in liquid form at a minimum temperature of -34°C. It was known that the ground temperature is about 6°C the year around (see Quinteros et al. 2019) and it took about 1 month to freeze the ground. Figure 4 shows a frozen sample obtained at Øysand.

Figure 4. Frozen core sample of gravelly sandy Øysand soils.

4. Assessment of sample disturbance of piston samples

Disturbance of samples obtained by piston sampling was qualitatively and quantitatively assessed by means of (a) recovery ratio, (b) visual inspection, (c) density variations, and (d) particle orientations. The last three analyses were possible thanks to µCT-scan technology and image analysis of randomly selected cross-sections along the tubes.

4.1. Recovery ratio

Values of the recovery ratio are shown in Figure 5, where the recovery ratio is plotted against sample depth. PSØ54 samples have an average recovery ratio of 0.78, whereas the few PSØ72 samples obtained show an average value of 0.33. The two samples obtained with the GPSØ71 sampler have values of 0.22 (due to a cobble found in the BH) and up to 1.0 at shallow depth. A recovery ratio of at least 0.8 is usually targeted in common practice. Indirect assessment of sample quality based on the recovery ratio indicates that the GPSØ71 is able to obtain a large volume of soil, followed by the PSØ54. Note that both PSØ54 and GPSØ71 have a core catcher, while the PSØ72 does not and is not recommended for sampling sand, but it is suitable for silt and clay.

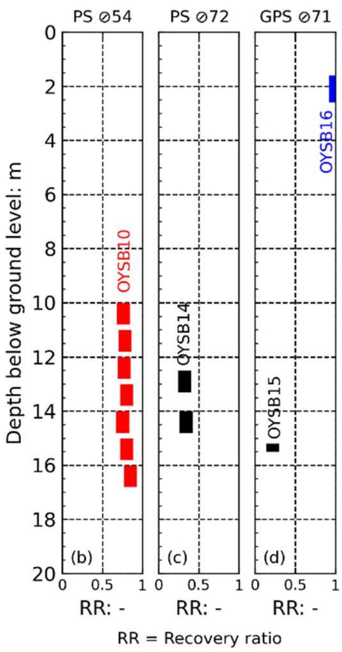

Figure 5. Samples obtained versus depth: (a) PSØ54 samples, (b) PSØ72 samples, and (c) GPSØ71 samples.

4.2. Visual Inspection

µCT scanning was used to visually assess the disturbance. The scanner used in this research is a Nikon Metrology XT H-225 LC device, located at NGI in Oslo, Norway. The beam of X-rays generated is conical and polychromatic. The maximum voltage is 225 kV and the maximal current is 500 µA. The source of this scanner allows a minimum voxel size of 3 µm (spot size), which implies that, theoretically, at maximum resolution almost all silt particles could be observed. Thousands of radiograms (>1500) obtained during a single µCT-scan were reconstructed using the filtered back projection technique to a 3D volume by the software VG-Studio Max (volumegraphics.com).

Given the Øysand soil's non-trivial PSD, mineralogy and the dimensions of the tube samples scanned, the voxel resolution achieved depended on the scanning parameters used. Parameters used such as voltage, current, magnification, voxel size, number of projections, and frame average of all scans are summarised in Table 1. Given the variability of soils scanned, the presence of water and fines contents within the soil, the sample tube material (steel or composite), different scanning parameters were used for different samplers. Note that zoomed (close-up) images with higher voxel sizes were also obtained from each tube for a more detailed image analysis.

Table 1. Scanning parameters used

Sampler	Voltage / Current	Voxel Size	Number of projections
PSØ54	97 / 36	121 / 48	2500
PSØ72	210 / 215	118 / 45	3142
GPSØ71	225 / 110	119 / 42	3142
Ground freezing			

2D cross sections of the CT-scans are presented in Figure 6. Two PSØ54 samples are shown in Figure 6a and b, PSØ72 samples in Figure 6c and d, and GPSØ71 samples are shown in Figure 6e and f. Some general qualitative observations about the soil layering can be made from visual inspection of the µCT scan images presented in Figure 6 and zoomed images presented in Figure 7: (i) Severe disturbance in the form of cracks can also be seen in Figure 6a, b and c, (ii) dipping of soil layers are about 20° to 25°, which may be a result of the depositional history of the soil at the site, (iii) air pockets within soil and especially on the sides of the tube walls of PSØ54. Finally, (iv) bending of soil layers is observed for the PSØ72 sample between 12.5-13.3 m depth (Figure 7b). Based on visual inspection, it seems that the least disturbed piston samples are the ones obtained using the GPSØ71 sampler.

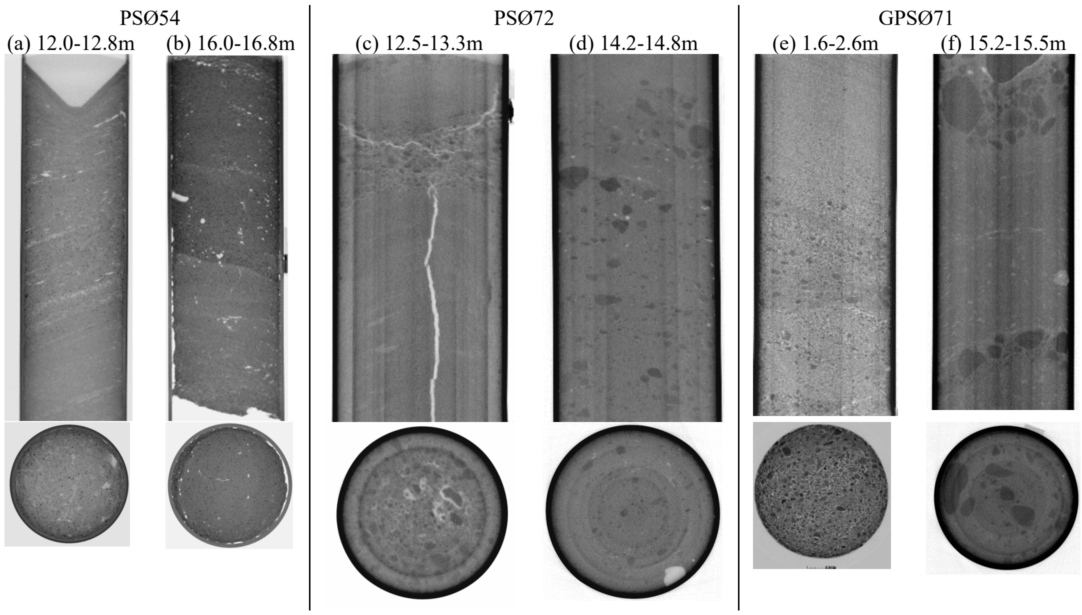

Figure 6. µCT of soil samples obtained by push pistons: PSØ54 (a) and (b), PSØ72 (c) and (d), GPSØ71 (e) and (f).

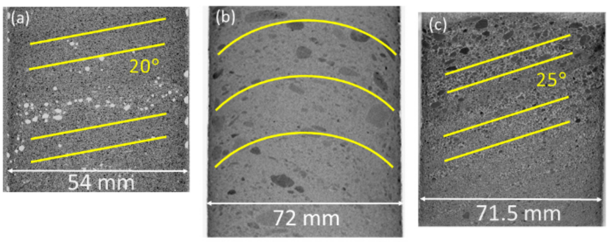

Figure 7. Assessment of sample disturbance by visual observation: (a) PSØ54 at 16.4m depth, (b) PSØ72 at 14.1m depth, and (c) GPSØ71 at 2.5 m depth.

Note that almost all of the PSØ54 samples showed a considerable amount of air pockets (see Figure 8, where air pockets are highlighted). These air pockets might have resulted from a combination of sampling issues such as the high friction possibly developing between the rough composite liners and the soil and/or aspects related to sample storage. More rounded air pockets might be the result of gas produced by bacterial decomposition and may not be attributed to sampling disturbance. Note that the PSØ54 soil was sampled earlier than their PSØ72 and GPSØ71 counterparts. Thus, the PSØ54 samples were stored for a period of about 3 months before being µCT-scanned.

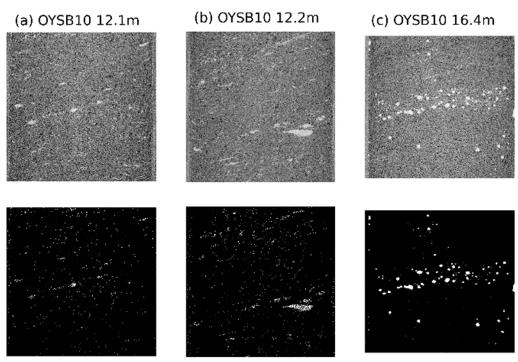

Figure 8. Air pockets observed on PSØ54 samples.

4.3. Density

Changes in density were assessed indirectly on cross-sections of the soil samples. The grey scale of the images was used as a proxy for qualitative assessment of variation of density, as done for instance in Frost & Park (2003). The uniformity of soil density was analysed by assigning the pixels a value of zero for black (dense matter) and 255 for white (voids) for the chosen grey scale. Therefore, the lower the grey scale value (darker), the denser the soil, and vice versa for the high grey values or loose soil. Note that a limitation of this method is that the cylindrical tube specimens have an uneven and dispersed X-ray distribution (X-rays in the specimen centre must pass through more soil, than at the edges). Hence, the results are to be taken only as a general indication of density changes and not as absolute values. These indirectly assessed density variations, calculated as grey value changes, are shown in Figure 9.

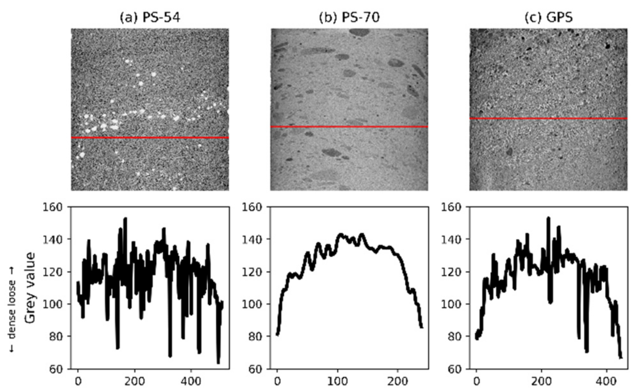

Figure 9. Indirect assessment of density across the piston samples (the lower the grey value, the lower denser the soil): (a) PSØ54, (b) PSØ72, and (c) GPSØ71.

Sampling seems to have induced densification near the edges regardless of the sampler used. The distance of the disturbed soil from both edges for each sampler is equal to 1/2 times the sample diameter for PSØ54, about 1/5 for PSØ72 and 1/8 for the GPSØ71. The disturbance higher disturbance of the PSØ54 sampler may be attributed to the roughness of the composite liner.

4.4. Analysis of particles orientation

Particle orientations were assessed using the zoomed CT-scan images. Due to the wide range of particle sizes and the complex mineralogy of Øysand soil, automatic segmentation was challenging, i.e., silt particles could be incorrectly recognized as part of sand grains by automatic segmentation algorithms, thus compromising the original shape of grains. Therefore, manual segmentation (using the software ITK-snap after Yushkevich et al., 2006) was employed to obtain segmented images on selected 2D cross-sections.

Particle longest axes orientations were calculated from some segmented particles within the centre of the piston samples and at the edges interface between the soil and the piston tube wall. An example of the binarization and segmentation process for a GPSØ71 scan is given in Figure 10. The goal of this analysis was to identify any induced orientation changes of soil particles within the sampling piston and close to piston walls.

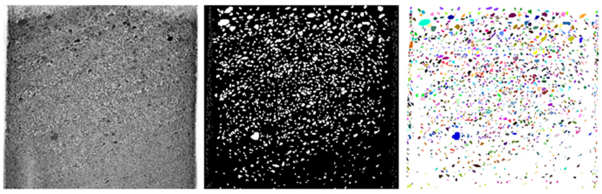

Figure 10. Typical workflow for image analysis: (a) original image, (b) binarization, and (c) segmentation.

Rose diagrams of particles orientations at the centre and edges for the three samplers used are shown in Figure 11. The Rose diagrams' shading in Figure 11 corresponds to the particle's long axis orientations of selected particles within the centre and edges of the pistons.

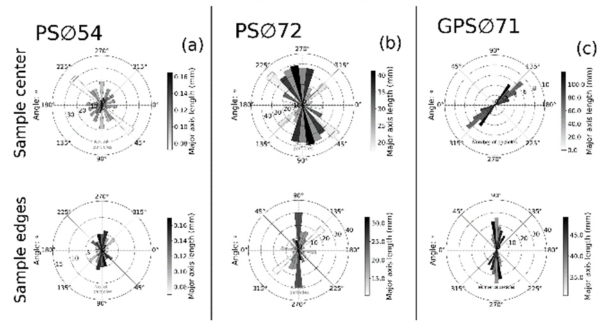

Figure 11. Long axis orientations of selected particles within the centre and edges of the piston for the three different samples: (a) PSØ54, (b) PSØ72, and (c) GPSØ71.

Note that particles within the centre are not oriented in the same way as particles close to the edge of the piston tubes. Particles located in the centre of the soil sample show either a more varied distribution of angles in the case of PSØ54 and PSØ72 and a very distinctive dipping in the case of the GPSØ71, which may possibly correspond to the soil layering orientations. On the other hand, particles close to the soil-tube wall interface tend to rotate towards the vertical possibly to re-align themselves with the piston tube penetration direction (vertical) into the ground.

5. Assessment of sample disturbance of frozen soil samples

From visual observations of the surface of cored frozen soil samples shown for instance in Figure 4, no ice lenses were present within the specimens, no rotation of gravelly/sandy particles were observed on the samples edges, and, finally, no cracks had formed within the frozen soil masses.

As described in detail in Quinteros & Carraro (2023), the diameter of the cored frozen soil was D=103 mm. To obtain a higher image resolution in the μCT for image analysis, frozen specimens of D=25.3 mm and 31 mm in height (H) were sub-cored using a diamond drill bit mounted inside a temperature-controlled room at -9°C to avoid thawing. Particle orientation analyses were conducted using 2D cross-sections in perpendicular planes of 0° and 90° across the scanned cylinder of frozen soil (see Figure 12). As seen in Figure 12, despite of the sub-coring process of the frozen samples, particles in the edges of the frozen sand seems to not have experience any rotation when compared with particles within the frozen ground. No air bubbles were observed in the frozen soil samples.

(a) 0° cross section (b) 90° cross section

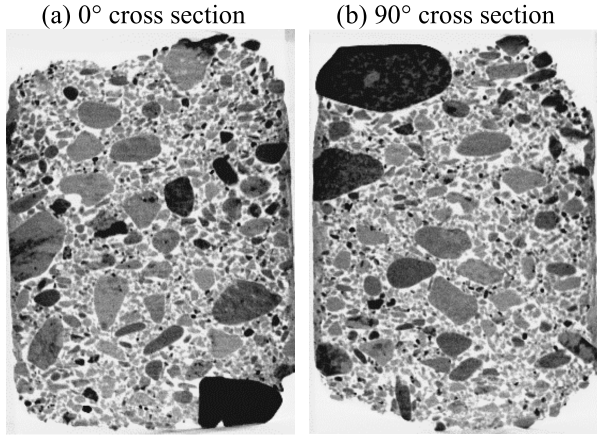

Figure 12. Vertical cross sections from the 3D volumes obtained using μCT on frozen soil: (a) at 0° and (b) at 90° scanning degrees.

To obtain particle orientations, high-quality ground-truth segmentation was performed on 2D cross sections. Rose diagrams of major particle axis orientations are presented in Figure 13. Shading grey scales on the diagrams depict major particle axis length in mm. The bias for the major particle axis orientations of larger particles in the frozen soil can be observed by comparing the Figure 13a with Figure 13b. These two plots show that the larger particles of cross-section 90° (Figure 13b) are more oriented along the horizontal than their counterparts in cross-section 0° (Figure 13a), possibly due to the fluvial depositional history of the site. Detail 3D analysis of particle orientation, anisotropy, void ratio and particle size distributions of the frozen soil are presented in Quinteros & Carraro (2023).

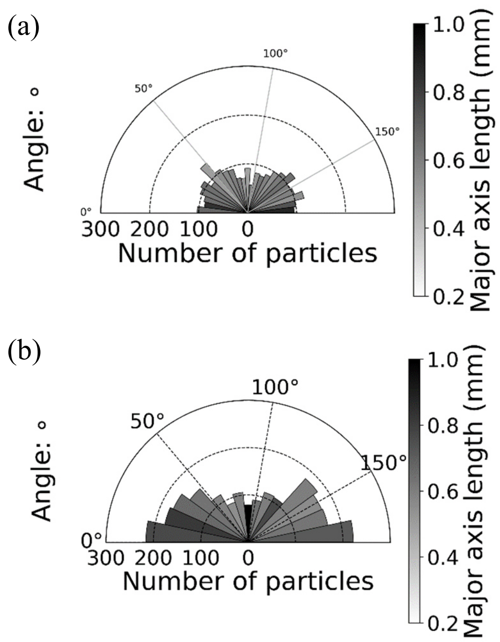

Figure 13. Particle orientations: (a) for 2D cross-sections 0°, and (b) for 2D cross-section at 90°.

6. Remarks on sample disturbance

Sampling sandy soil using piston technology at Øysand was extremely difficult. The main issues faced, together with comments on the sample disturbance for each sampler can be basically summarised as follows:

- The PSØ54 was able to recover soil samples at Øysand. The small sampler diameter and core catcher associated with this device are responsible for the high recovery ratio observed. Nevertheless, severe disturbance in form of air pockets, densification and rotation of particles near the tube walls was observed.
- Due to the lack of a core catcher, very few samples were obtained using the PSØ72. Severe disturbance of silty layers was observed in form of cracks and some air pockets, together with bending of the soil layers and densification. Moreover, rotation of the particles close to the interface between the soil and the tube wall edges was also observed.
- Due to the technical difficulties and the presence of gravel and cobbles in the soil layers sampled, very poor recovery was obtained with the GPSØ71. Nevertheless, the recovery ratio and sample quality were better than those observed for the other two conventional piston samplers (PSØ54 and PSØ72). No bending of the soil layers, slight particle rotation and minimal densification of the soil close to the tube wall interface were observed. Nevertheless, sampling gravelly soils at Øysand using the GPSØ71 was challenging.
- For the undisturbed specimens obtained by ground freezing no disturbance was observed. Moreover, a bias of particle orientation is inferred by comparing the orientation of the particles between two perpendicular cross-sections. This preferred concentration of major particle axis orientations may be the result of past fluvial depositional/flow processes at the site. In general, frozen samples should be considered as the standard that the piston samples should be compared against.

In general, the piston sampling campaigns at Øysand had limited success. Ground freezing for sampling was considered as an alternative option for obtaining high quality sand samples, which allowed a more detail analysis of the soil fabric.

7. Conclusions

State-of-the-practice and state-of-the-art *in situ* characterisation techniques have been used to investigate stratigraphy and to derive some engineering parameters for the Øysand soils. Moreover, attempts for sampling Øysand sand layers using state-of-the-practice (PSØ54 and PSØ72) and state-of-the-art (GPSØ71) piston samplers were presented. Insights from the sampling campaigns performed include:

- Piston sampling at the Øysand site was extremely challenging, mainly because of the gravelly particles found within the sand layers in the top soil unit. Gravelly layers restrained the penetration of the samplers and damaged the edges of the tubes or cutting shoes. The use of a core catcher is highly recommended to achieve a better sample recovery. Based on the qualitative and quantitative sample disturbance analysis of the very few samples obtained, which was carried out using μCT image analysis techniques, it is noted that the GPSØ71 imposes the least amount of disturbance on the sampled soil, while both push piston samplers, PSØ54 and PSØ72, caused more soil disturbance.
- Visual inspection of the frozen Geofrost coring sand samples using X-ray imaging detected coarse gravel particles, seams of gravelly sand and silt layers within the frozen sand mass. However, no significant ice lenses, cracks, or rotation of edge particles were observed, which was an encouraging indication of sample quality.

In practice, ground freezing is recommended to obtain high quality undisturbed samples, and as a secondary option the gel-push sampler for silty sands.

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