

Mechanical and micro-CT study of frost-heave in silty sands

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ABSTRACT

Soil freezing occurs naturally in cold regions where it affects many aspects of geotechnical practice and infrastructure. Moreover, artificial ground freezing can be used to stabilize sandy and silty soils prior sampling, but also as stabilization measure in tunnelling and open excavations. This paper reports a laboratory-based study on the frost-heave response of four silty sand soils from the Øysand Norwegian geotechnical test site. The combined effects of fines content and vertical effective stresses were investigated in a one-dimensional cell with parallel micro-computed tomography to assess the impact of a freeze-thaw cycle. As expected, the higher the fines content the higher the expansion noted on freezing and increasing the vertical effective stress reduced or eliminated frost-heave, the stress levels required to suppress heave increasing with fines content. Additionally, micro-CT image analysis added important further insights and shows that freezing may disturb the soil fabric, even when the resulting global strains are too small to measure by conventional means (using an LVDT). The experiments provided crucial evidence regarding the circumstances under which ground freezing could be an effective aid to low-disturbance sampling in silty sands and provides useful information for other geocryological engineering applications in such strata.

1. Introduction

Ground freezing for sampling, is used to minimize soil disturbance during coring, transportation, storage, trimming and mounting of sandy or silty specimens in advanced geotechnical testing apparatuses in the laboratory. However, freezing can also disturb the initial depositional fabric and cause plastic deformations if the soils are frost susceptible. While freezing for sampling techniques have been successfully employed for clean sands (Yoshimi et al., 1977, 1984; Sego et al., 1994; Wride et al., 2000; Hofmann et al., 2000; Ghionna et al., 2001), the effects of non-plastic silt, which could increase their frost-heave susceptibility, has not been reported in length.

It is generally known that volumetric expansion of the soil's pore water take place when the soil mass freezes. The pioneering work on frost susceptibility of soils of Taber (1929, 1930) in the USA and Beskow (1935) in Sweden, showed that depending on the vertical effective stress (σ'_v) applied, water can be attracted to or expelled and frost-heave may or may not occur. Since then, the factors that affect soil expansion during

freezing have been explored comprehensively by multiple authors (see Yoshimi et al., 1978; Landay, 1985; Vinson et al., 1986; Andersland and Ladanyi, 1994; Tester and Gaskin, 1996; Konrad and Lemieux, 2005; Konrad, 2008; Andersland and Ladanyi, 1994). As shown schematically Fig. 1, particle size distribution (PSD), cooling temperature, suction, permeability, σ'_v , relative density (Dr), and salinity all affect frost heave and creep rates.

Using a one-dimensional freezing testing apparatus, Yoshimi et al. (1978) investigated the frost susceptibility of three clean sands ($C_u = 1.3$ – 1.9) and observed a linear decrease of frost-heave expansion with a logarithmic increase of σ'_v . Under σ'_v around 0.3 kPa, very dense ($Dr = 90\%$) Toyoura and Niigata sands expanded by about 0.5 % and 1 %, respectively. However, raising σ'_v to 7 kPa and 10 kPa for Toyoura and Niigata sands, respectively, apparently completely subdued frost-heave expansion for both sands. Similar observations were made by Da Roit et al. (1981), when freezing saturated medium-dense clean sand ($C_u = 1.2$, $Dr = 56\%$) at $\sigma'_v = 100$ kPa; they reported a “limited dilation well inside the elastic range”, which was apparently “recovered” during

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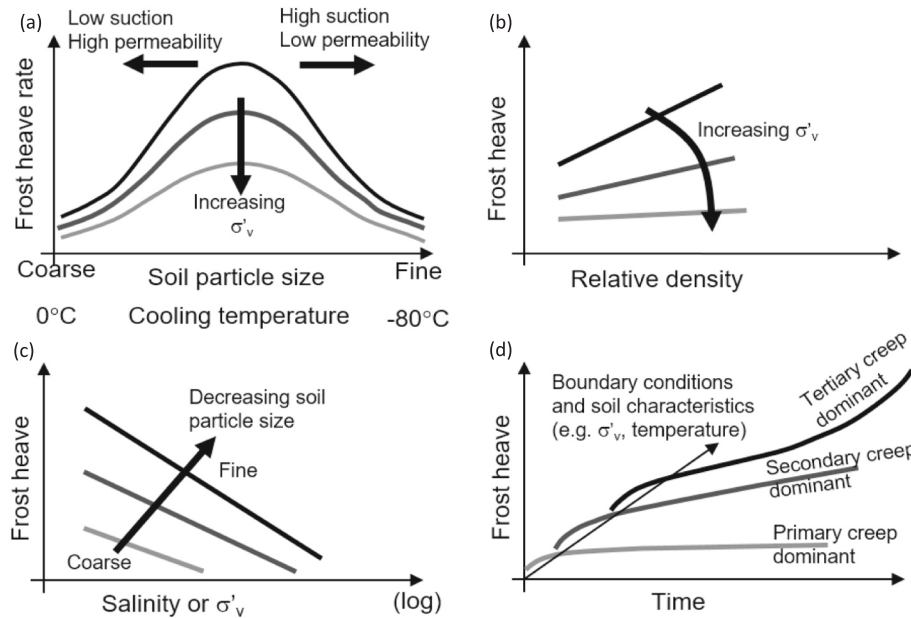


Fig. 1. Schematic effects of: (a) particle size and cooling temperature, suction, permeability and vertical effective stress (b) relative density and vertical effective stress, (c) salinity, particle size and vertical effective stress, and (d) creep on the frost-heave behaviour of soil (see for instance Yoshimi et al., 1978, Landay, 1985, and Andersland and Ladanyi, 1994).

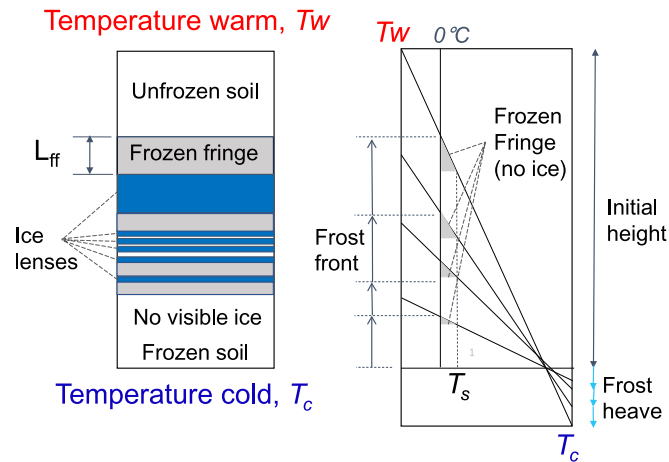


Fig. 2. Illustration of ice lenses formation in soil (from Konrad and Morgenstern, 1980).

thawing.

Konrad and Morgenstern (1980, 1981, 1982a, 1982b) introduced a thermo-hydraulic model to describe ice lens formation. They showed experimentally how temperature gradients and σ'_v affect frost-heave susceptibility in soils. Konrad and Morgenstern (1982b) observed that ice tends to appear behind the freezing front, which is the warmest isotherm before water transforms to ice, as shown in Fig. 2. The ice lens thicknesses depend on the temperature gradient around the segregated ice as the soil changes in temperature from warm (T_w) to cool (T_c). The segregation-freezing temperature (T_s), which is the temperature at the interface between the ice lens and the frozen fringe, determines the thickness of the frozen fringe (L_{ff}), and the thickness of ice lenses, see Fig. 2. Segregation potentials vary from soil to soil, as a function of parameters including fines content (FC) and σ'_v . Konrad and Morgenstern (1982b) postulated that the higher σ'_v , the lower T_s , the thicker L_{ff} and the greater the restrain on frost heave (see Fig. 3). Frost-heave expansion is suppressed or subdued once a certain vertical stress ($\sigma'_{v, sub}$) is exceeded. However, as pointed out by O'Neill and Miller (1985),

ice can continue forming inside the fringe as suctions attract more water. Nowadays, comprehensive Thermal-Hydro-Mechanical (THM) models exist that can capture all of these features within a critical state framework, e.g. Nishimura et al. (2009).

Recent research linking the macroscopic frost heave and thaw behaviour with the microscopic pore structure, using micro-CT scanning, has focussed mainly on clayey soils (Wang et al., 2017; Fan et al., 2021; Nishimura et al., 2021; Amato et al., 2022; Fan et al., 2024), silty clayey soils (Liu et al., 2019), or stabilised loss with cement (Wang et al., 2016; Liu et al., 2024).

Artificial ground freezing for sampling can be used to decrease sampling disturbance of sandy and silty soils. However, soil heave and associated thawing strains may cause detrimental damage and deserve attention in geotechnical engineering. This paper reports ground freezing experiments on four sandy silty soils, adding new data to the earlier studies, and presents novel micro-Computer Tomography (μ CT) observations of the associated local fabric changes and other key phenomena of soil disturbance induced by a freezing-thawing cycle.

The specific purpose of this research was to assess the frost-heave susceptibility of soils at the Øysand Norwegian geotechnical test site near Trondheim (Quinteros et al., 2019), and to determine whether frost-heave expansion during ground freezing was recoverable after thawing. Assessing the suitability of ground freezing for sampling was a byproduct of this study. The effects of soil fines and vertical stresses were investigated through laboratory experiments conducted in a temperature-controlled cell on specimens reconstituted at dense states. Frost-heave expansion was measured accurately and changes in the soils' fabrics were qualitatively assessed by means of μ CT scans before and after freezing-thawing cycles.

2. The Øysand research site

The soils tested in this study were sampled from the Øysand research site near Trondheim in Norway, which was established through the Norwegian Geo-Tests Sites (NGTS) project (L'Heureux et al., 2017). The goal of the NGTS project was to extensively characterise five sites, namely, a gravelly silty sands at Øysand (Quinteros et al., 2019), silt at Halden (Blaker et al., 2019), soft clay at Onsøy (Gundersen et al., 2019),

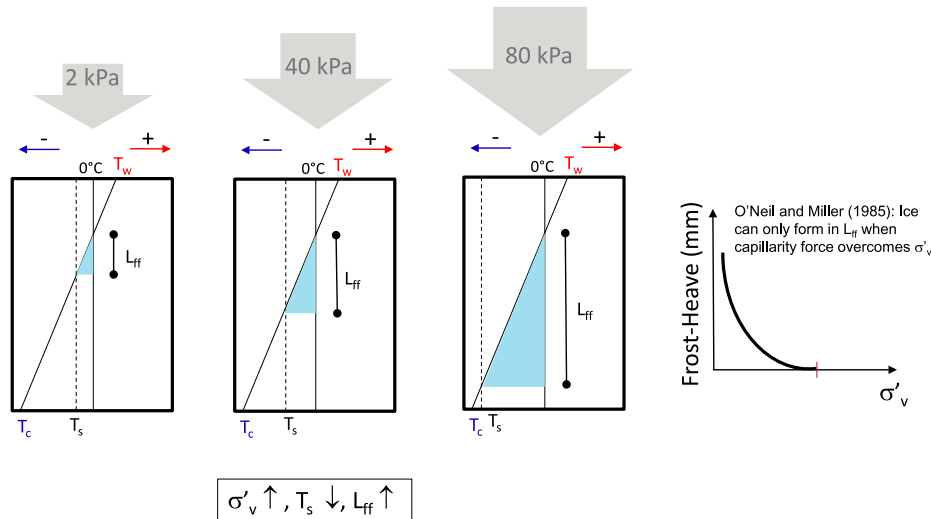


Fig. 3. Schema of the influence of vertical effective stress on the segregation temperature (T_s) and frozen fringe (L_{ff}).

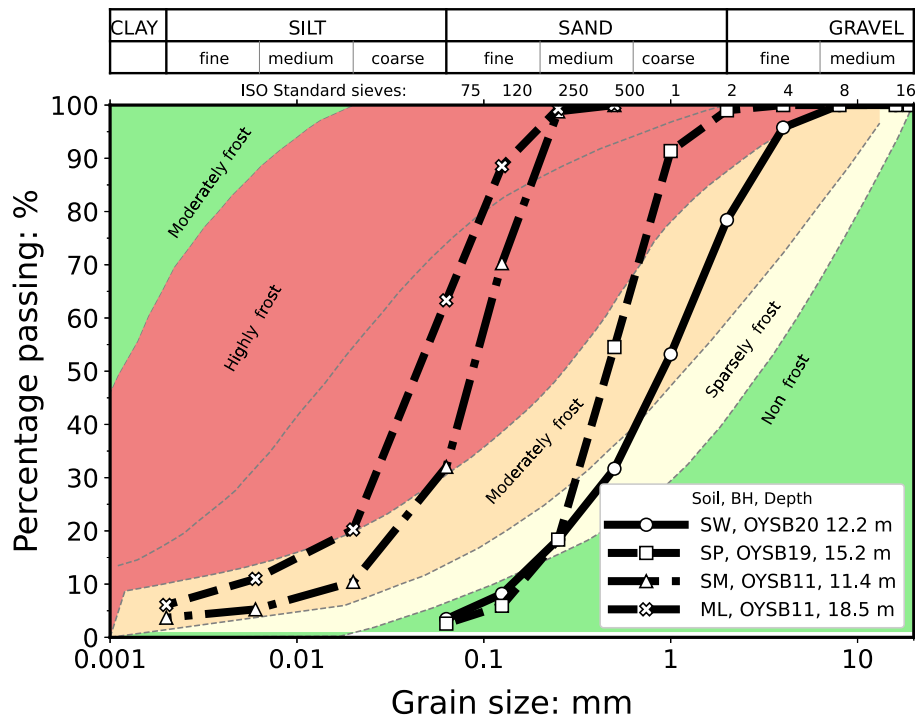


Fig. 4. Particle size distributions of the Øysand soils tested in this study against the frost susceptibility guidelines of the Norwegian N200 (2014) recommendations.

quick clay at Tiller/Flotten (L'Heureux et al., 2019), and permafrost in Longyearbyen, Svalbard (Gilbert et al., 2019). The sites are open to the geotechnical community worldwide.

The Øysand sands originate from the Gaula, a 150-km-long river which flows into Trondheimsfjord. The deposits consist of fluvial soil layers, underlain by deltaic and marine sediments. Following deglaciation of the region approximately 10,300 years ago, the Øysand area was subjected to glacio-isostatic rebound and fall of relative sea level. The highest relative sea level of the area is approximately 175 m above the current sea level (m.a.s.l.) (Reite, 1994). The mouth of the Gaula River continuously moved in a north-westwards direction throughout the Holocene, in phase with delta progradation. The coarser deltaic and fluvial sediments deposited directly on the seafloor, consisted mostly of silts and clays (marine deposits). The deposits currently encountered at Øysand were produced by glacial erosion of the bedrock and fluvial

erosion of marine and glacial deposits in the catchment area. In general, the stratigraphy down to 20 m below ground surface can be divided into two main units: a coarse to gravelly sand (fluvial deposit) from 0 to 10 m, and a lower unit consisting mostly of fine silty sand (deltaic soils) from 10 to 20 m depth. 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.

3. Initial frost-heave susceptibility assessment for Øysand soils

A raw assessment of frost susceptibility can be made by comparing its PSD against the one of soils known to be frost susceptible. In general, gravelly soils are non-frost susceptible whereas clays are moderately frost susceptible. In between, silts and sandy silts are highly susceptible to frost, whereas sands are moderately to sparsely frost-heave susceptible.

Table 1
Physical characteristics of Øysand soils tested.

Soil symbol (ASTM D2487)	SP	SW	SM	ML
Sampling depth: m	15.2	12.2	18.5	11.4
Particle diameter at 10 % passing, D_{10} : mm	0.157	0.118	0.020	0.005
Particle diameter at 30 % passing, D_{30} : mm	0.310	0.340	0.056	0.026
Particle diameter at 60 % passing, D_{60} : mm	0.554	0.790	0.010	0.058
Coefficient of uniformity, C_u	3.5	6.7	5.2	12.0
Coefficient of curvature, C_c	1.1	1.2	1.5	2.5
Fines content (< 0.075 mm), FC: %	~2	~6	~41	~69
Specific Gravity of soil solids, G_s (ASTM D854–14, 2014)	2.70	2.71	2.71	2.70
Maximum void ratio NGI method, $e_{max,NGI}$ (Lunne et al., 2019)	0.831	0.723	1.347	1.552
Minimum void ratio NGI method, $e_{min,NGI}$ (Lunne et al., 2019)	0.487	0.384	0.612	0.693

A myriad of guidance and standards exists, which can opaque such assessments as soils are classified in broad categories (Chamberlain, 1981). General rules are outlined, for example, by the Norwegian (N200, 2014) recommendations, the German frost susceptibility classification system (Floss, 1997), the U.S. Army Corps of Engineers system (Johnson et al., 1986), the Canadian Department of Transport (Armstrong and Csathy, 1963), the US Federal Highway Administration (FHWA) in the National Cooperative Highway Research Program (NCHRP (National Cooperative Highway Research Program) 1-37A, 2022) or the International Society for Soil Mechanics and Foundation Engineering (ISSMFE-TC8, 1989). According to such classifications, the Øysand sandy soils classify as moderately to sparsely frost susceptible, while the silty sand and silt layers rate as being highly frost susceptible. Fig. 4 shows the PSDs of Øysand soils compared to the Norwegian guidelines (N200, 2014). Nonetheless, PSD comparisons alone do not consider other crucial factors that influence frost susceptibility, such as $Dr.$, σ'_v , salinity, cooling rate, among others.

In this research, the frost-heave expansion and permanent thawing deformations of four Øysand soils with different PSDs and FCs, prepared at $Dr. \approx 80\%$, were investigated in a one-dimensional temperature-controlled cell, at a range of σ'_v values, under a gradient temperature comparable to those expected to develop in the field during ground freezing for sampling. σ'_v was increased to determine the stress level needed to subdue frost-heave expansion (σ'_{v-sub}). In turn, this allowed

estimation of the depth below which ground freezing can be safely used to avoid sample disturbance, so that the in-situ fabric is preserved. The main goals of this experimental programme were: (i) to determine whether the Øysand soils tested are frost susceptible and, if so, (ii) measure whether the heave expansion caused by freezing is reversible when the soil is thawed, (iii) assess the effects of σ'_v and fines content on the heave expansion and thaw-induced settlement, and, finally, (iv) to evaluate whether ground freezing is suitable to core undisturbed soils, as well as the depths at which the freezing technique may work best in the field.

4. Methodology

The four Øysand soils tested are classified as well graded sand (SW), poorly graded sand (SP), silty sand (SM), and silt (ML) after ASTM D2487 (2017). The PSDs and physical characteristics of the soils tested are shown in Fig. 4 and Table 1, respectively. As shown in Table 1, the soils tested have different FCs, or percentages of particles < 0.075 mm (ASTM D2487, 2017). Specimens were reconstituted and consolidated to values between $\sigma'_{v,c} = 2.7$ kPa and 140 kPa, which are equivalent to the depths at which ground freezing was planned to be conducted in the field, then a single cycle of freezing and thawing was applied.

4.1. Equipment

The experimental setup used in this study was housed inside an environmental room. The setup comprises a temperature-controlled cell that could impose one-dimensional freezing-thawing cycles. The cell features three independent thermostats that are used to impose temperatures to the top, bottom and periphery of the specimen located inside the cell. Fig. 5 shows the complete experimental setup. Each component of the apparatus is discussed below in detail.

4.1.1. Environmental room

The environmental room is located at the Norwegian Geotechnical Institute (NGI) in Norway, Oslo. The environment room is 3 m long, 2 m wide and 2 m high. It can maintain: (i) a temperature ranging from -10.0°C to $+40.0^\circ\text{C}$, (ii) with $\pm 0.25^\circ\text{C}$ accuracy, and (iii) temperature differences within the room no greater than 0.5°C when above zero, and 0.75°C when below zero. A constant temperature of 3°C was used in the room when assembling the cell (i.e., connecting hoses and

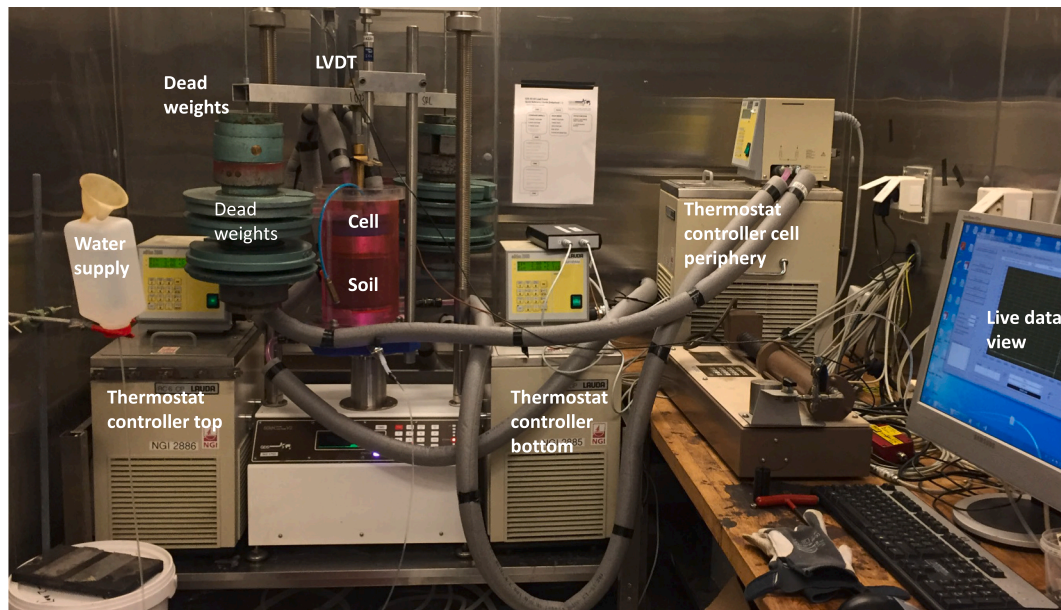


Fig. 5. Experimental setup.

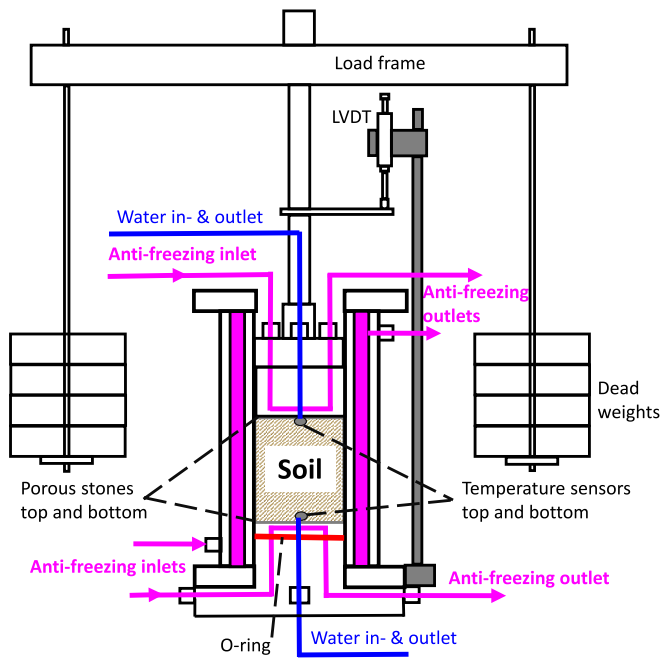


Fig. 6. Sketch of the temperature-controlled cell used (modified from Jin et al., 2019).

burette for water supply, and mounting displacement transducers), and throughout the testing, from setting the initial soil temperature through to the final dismantling of each sample after a freeze-thaw cycle.

4.2. Temperature-controlled cell

A special cell, sourced by the Korean Institute of Civil Engineering and Building Technology (KICT), was used to freeze the soil. Details of the cell development and its components are found in Jin et al. (2019). A schematic sketch of the KICT cell is shown in Fig. 6, whose most important features are:

- A transparent cell made of a pair of concentric acrylic cylinders. The wall of each cylinder is 10-mm thick, and a gap of 10 mm exists between the cylinders. Anti-freezing liquid is circulated in the gap between the cylinders. By connecting the cell anti-freezing liquid to a thermostat, the cell periphery temperature is controlled. The inside diameter of the cell is equal to 99.72 mm, which defines the diameter of the soil specimen to be tested.

Table 2
Summary of frost-heave tests results.

Test		Initial	Flushing	Consolidation	End of freezing	End of thawing	Freezing boundary conditions					
Soil	σ'_v : kPa	H_i : mm	Dr_i^* : %	Dr_s^* : %	Dr_c^* : %	$\Delta e_{a,f}^*$: %	Dr_f^* : %	Δe_{at} : %	Dr_t^* : %	ΔT^{**} : °C/mm	T_{top} : °C	T_{bot} : °C
ML	2.7	101	80	84	84	-11.7	59	6.8	75	0.120	2.9	-9.2
	70	100	80	85	92	-2.2	87	3.5	95	0.125	2.8	-9.1
	140	105	69	74	89	-0.9	87	1.9	91	0.125	2.7	-9.3
SM	2.7	99	84	84	84	-6.0	70	3.1	77	0.118	2.8	-8.9
	4	100	80	81	81	-5.1	69	4.3	79	0.120	2.8	-9.1
	70	99	80	81	85	-0.5	84	0.9	86	0.120	2.8	-9.0
	140	100	81	82	86	0.0	87	0.2	87	0.118	2.9	-8.7
SW	2.7	100	80	80	80	-2.2	67	1.9	76	0.121	2.8	-9.3
	70	100	80	80	81	-0.5	79	0.2	79	0.122	2.8	-9.4
	140	101	78	81	81	-0.1	80	0.0	81	0.123	3.5	-9.3
SP	2.7	100	76	76	76	-1.8	64	1.6	71	0.121	2.9	-9.3
	70	101	80	80	80	0.0	79	0.0	80	0.128	3.6	-9.4
	140	100	80	80	78	0.0	78	0.0	78	0.127	3.0	-9.5

* subindices i , s , c , f , and t = Density at the end of saturation.

** ΔT = Temperature gradient ($T_{top} - T_{bot}$)/ H_c , where H_c = Height at end of consolidation.

- Top and bottom pedestals, made of a combination of aluminium and high-density-polyethylene (HDPE), have connections to allow independent circulation of anti-freezing liquid at each end. Top and bottom temperatures are controlled independently using two separate thermostats. This allows different temperature gradients to be imposed across the soil specimen height.
- Temperature sensors, placed at the top cap and at the bottom pedestal, are used to monitor the temperature as closely as possible to the soil specimen, and to apply the desired temperature gradient.
- Finally, a Linear Variable Differential Transducer (LVDT), calibrated at an ambient temperature of 3 °C, is used to measure axial deformations. The LVDT is manufactured by RDP-group and has a range of ± 50 mm, with a maximum error of 0.5 % at constant temperature of 3 °C. A maximum error of 0.05 mm, which was determined during calibration, was induced by changing the temperature around the sensor by ± 2 °C.

A pink-coloured ethylene glycol automobile anti-freezing liquid with a freezing point of -36 °C (commercially available as Xstream-G30 in Norway) was circulated inside the gap between the double-cell walls and inside the top and bottom pedestals. Two minor modifications of the KICT cell were made at NGL. First, the position of the rod used for attaching the LVDT was moved from the top to the bottom, attached to the base pedestal under the cell. A rigid connection between a rod used for hanging the LVDT and the base pedestal was made to avoid measuring any false deformation of the cell itself (Fig. 6). Second, a load frame was connected to the top pedestal to apply the surcharge loads. Since the loads needed to be kept constant throughout a test, dead weights were preferred, this being simpler and less affected by temperature variations than a closed-loop pneumatic system that relies on the feedback from a load cell.

Table 3
Scanning parameters used to obtain 3D μ CT scans.

Settings	Soil	
	ML/SM	SW/SP
Magnification	2.46	2.61
Voxel size: μ m	81	76
No. projections	1500	3142
Total rotation: °	360	360
Exposure time: s	1.0	1.0
Frame average	64	128
Voltage: kV	115	115
Current: mA	220	220

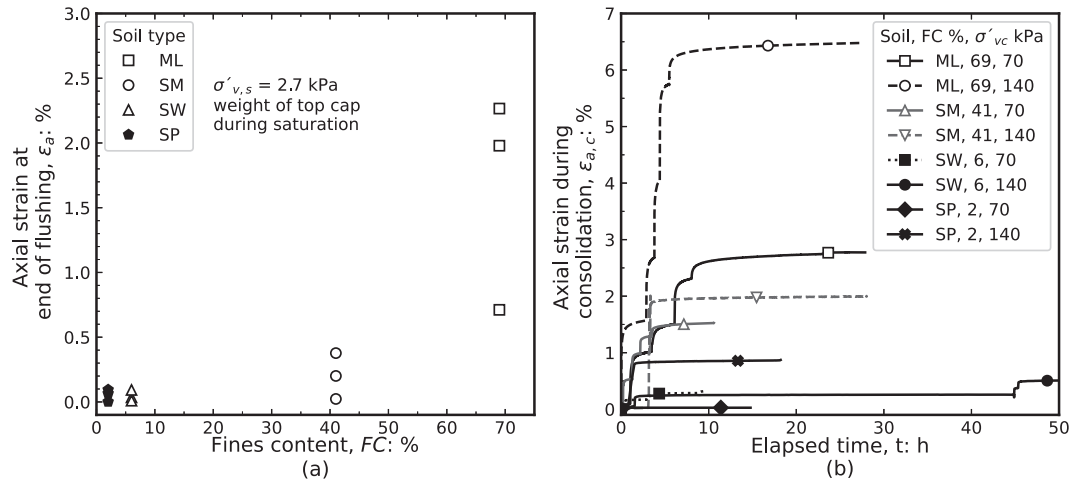


Fig. 7. Axial strain at (a) end of flushing, and (b) during consolidation for all soils tested.

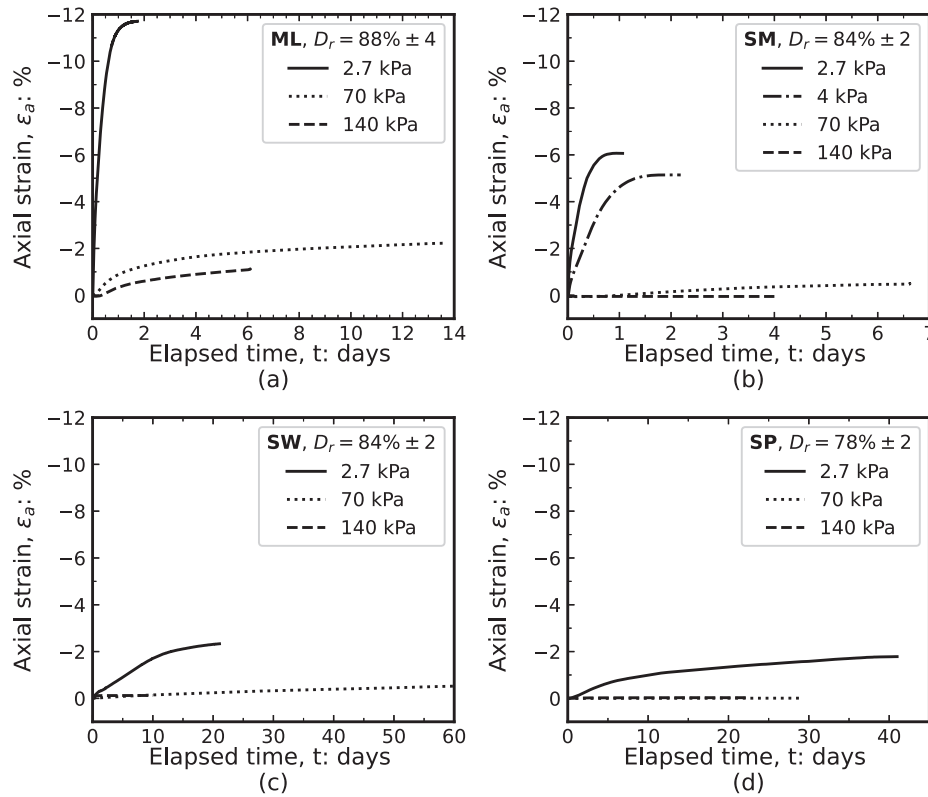


Fig. 8. Frost heave results for Øysand soils: (a) ML, (b) SM, (c) SW, and (d) SP.

4.2.1. Thermostats

Three thermostatically controlled pumps were used for independent control of the temperature on the top, bottom, and periphery of the soil specimen. The devices (produced by the German company Lauda GmbH and branded as ProLine) can pump anti-freezing liquid at a rate of 9 l per minute. Their temperature range of operation is -20°C to 160°C with a control variation of $\pm 0.1^\circ\text{C}$. The increase of temperature over time is

programmable, so that the rate of freezing can be specified and controlled.

4.3. Testing procedures

The specimens tested were reconstituted using the dry deposition (DD) technique, which involves funnelling dry sand through a long neck

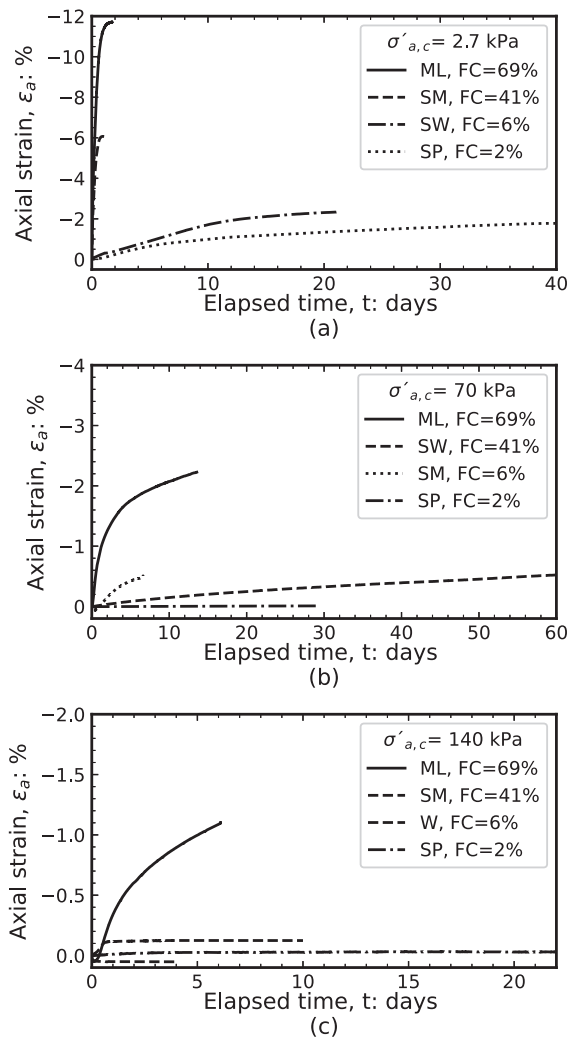


Fig. 9. Frost heave against elapsed time for different soil types at: (a) $\sigma'_{v,c} = 2.7$ kPa, (b) $\sigma'_{v,c} = 70$ kPa, and (c) $\sigma'_{v,c} = 140$ kPa.

funnel, while maintaining a constant fall height, as recommended by Ishihara (1996). Densification is achieved by tapping on the base pedestal around the cell using a rubber hammer, until the desired initial height was achieved. Specimen uniformity analyses were carried out and are discussed below. The specimen diameter was 99.7 mm and the target initial height (H_i) was 100 mm. The exact H_i values obtained for each specimen are presented in Table 2. The target relative density after consolidation (Dr_c) was 80 %, chosen as a conservative upper bound estimate of the in-situ Dr , based on Cone Penetration Tests (CPTu) profiling (see Quinteros et al., 2019). After specimen reconstitution, a filter paper, porous stone, and top pedestal were placed above the specimen and its initial height was measured 10 times and averaged by a calliper, the calliper resolution was 10 μ m. Using a μ CT-scanner (Nikon Metrology XT H-225LC scanner located at NGI in Oslo, Norway), the initial homogeneity of the reconstituted specimens was assessed. Table 3 shows the details of the parameters used for scanning. Giving the geometry of the specimens scanned (the whole cell was placed in the μ CT), the achieved voxel size was between 76 and 81 μ m; hence not sufficient

for a porosity analysis but enough for a qualitative assessment of density variations. Fine sand grains could be identified, but individual silt particles could not be resolved. After initial μ CT scanning, the cell was returned to the environmental room to precondition the soil specimen temperature, to an ambient temperature of 3 $^{\circ}$ C for at least 24 h. Subsequently, the LVDT, load frame and thermometer sensors were mounted, and the thermostats hoses connected to the cell top, bottom, and periphery. All thermostats were set to keep a constant temperature of 3 $^{\circ}$ C, and data logging initiated.

Specimen saturation was achieved by flushing 1 l of de-aired water from the cell bottom at a hydraulic gradient $i \approx 1$. The time needed to flush a specimen was about 3 h for the SW and SP soils, 12 h for the SM soil, and up to 24 h for the ML soil. When flushing was completed, water was set to about 2 cm above the top pedestal, so that enough water was let available to the specimen during freezing in case of ice formation.

Consolidation to the desired vertical effective stress was achieved by dead weight loading in incremental stages of about 10 %, 20 %, 40 % and 80 % and 100 % of the target final vertical effective stresses at consolidation ($\sigma'_{v,c}$). Once consolidation was completed, a freezing-thawing cycle was started. The specimen height after consolidation, H_c , was used as the initial height for calculating the axial strains induced by freezing, $\epsilon_{a,f}$, and at the end of thawing, $\epsilon_{a,t}$. Note that the axial strain is calculated by $\epsilon_a = \Delta L/H_i$, where ΔL is the change in axial displacement based on the LVDT measurements. As recommended by Jin et al. (2019), a uniform freezing gradient was achieved by setting the bottom thermostats to -10 $^{\circ}$ C, and the periphery at 1 $^{\circ}$ C, while the top cap was left at a temperature of 3 $^{\circ}$ C. Hence, achieving a temperature gradient of $\Delta T = 0.12$ – 0.13 $^{\circ}$ C/mm along the specimen height. ΔT is calculated as the ratio of the difference in temperatures between the top and the bottom of the specimen to the specimen height, e.g. (3 $^{\circ}$ C–(-10 $^{\circ}$ C)) / 100 mm = 0.13 $^{\circ}$ C/mm. This ΔT matches the recommended by the UK Transport and Road Research Laboratory (TRRL) (Crony and Jacobs, 1967).

The time needed to freeze a specimen varied between 24 h and up to 2 months, depending on the soil tested and applied stresses. Once $\epsilon_{a,f}$ reached a stationary value, thawing was started by setting the bottom pedestal and periphery back to 3 $^{\circ}$ C. The tests were terminated once the thawing $\epsilon_{a,t}$ vs. time curve flattened. At this point, the cell was carefully removed from the environmental room and placed again in the μ CT apparatus for final scanning. Comparison of the μ CT images after reconstitution and after a freezing-thawing cycle allowed for visual inspection of any possible soil fabric disturbances imparted by the freezing-thawing cycle.

5. Experimental results

Axial deformations were monitored closely during all test stages. Fig. 7a displays the average strains (ϵ_a) induced by flushing, which were $0.2 \% < \epsilon_a < 2.5$ %, and increased with increasing FC. The average axial strains recorded during dead weight consolidation, which stabilised within 24 h, are shown in Fig. 7b.

The average strain-time trends recorded as freezing was applied under up to four $\sigma'_{v,c}$ levels are presented in Fig. 8 per soil type. Note in that figure that:

- For the ML soil, marked frost-heave developed under $\sigma'_{v,c} = 2.7$ kPa that stabilised within a day. While the tests at $\sigma'_{v,c} = 70$ kPa and $\sigma'_{v,c} = 140$ kPa showed far less straining, their heaving process continued to progress actively after more than 6 days (Fig. 8a).

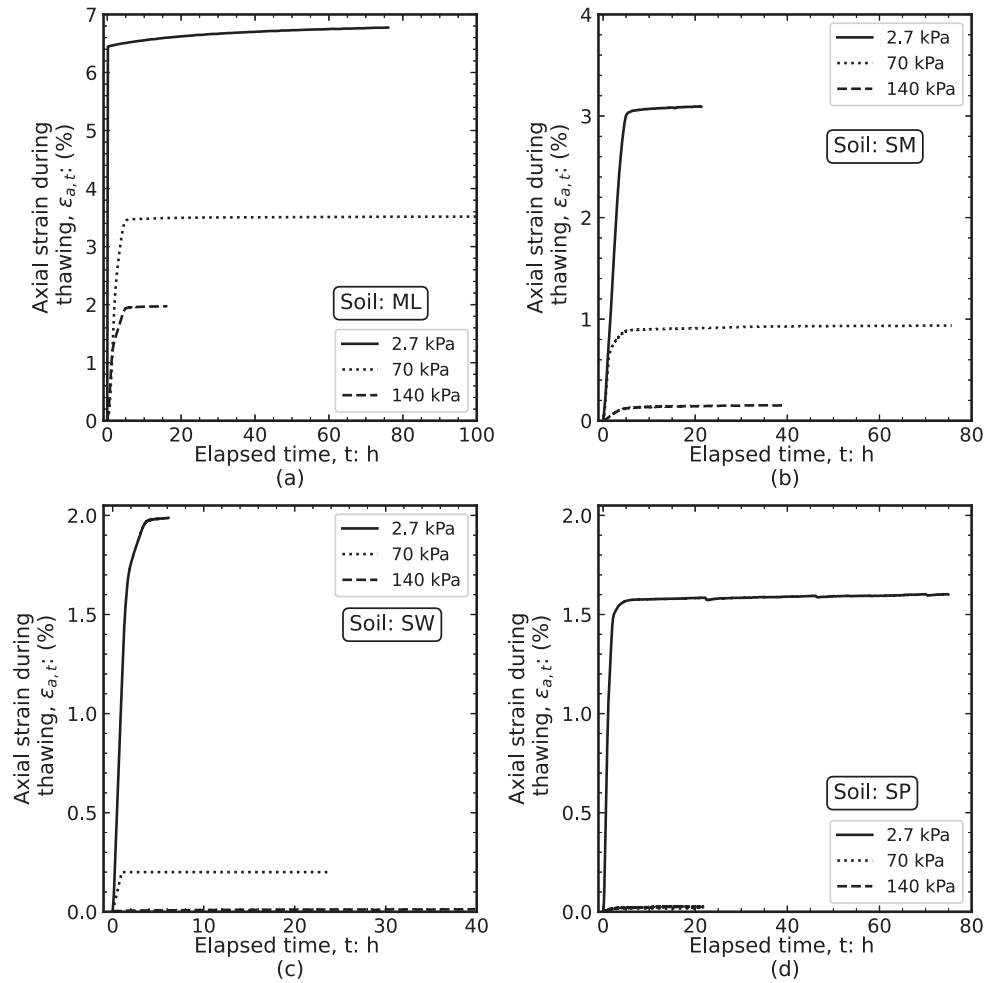


Fig. 10. Thawing results for Øysand soils: (a) ML, (b) SM, (c) SW, and (d) SP.

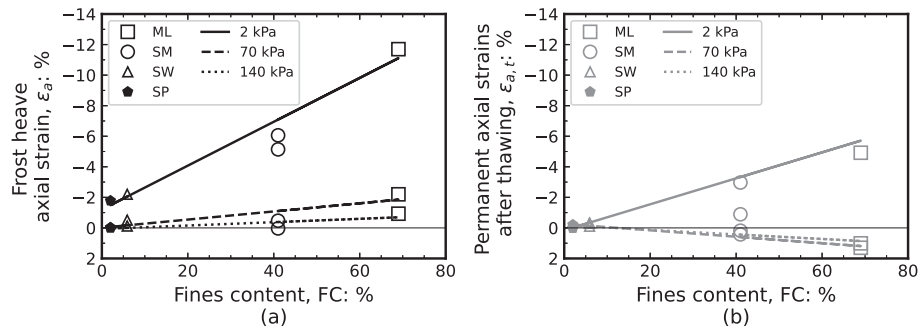


Fig. 11. Fines content effects on (a) freezing and (b) thawing axial strains of Øysand soils with respect to the vertical stress at consolidation.

- The $\sigma'_{v,c} = 2.7$ and 4 kPa for the SM soil showed frost heave stabilising after about 1 and 2 days respectively. While it took about 5 days for the test at $\sigma'_{v,c} = 70$ kPa to reach stable conditions (Fig. 8b), the 140 kPa test did not heave.
- The SW sand (Fig. 8c) required about 20 days to reach the end of its significant primary heaving under $\sigma'_{v,c} = 2.7$ kPa, although secondary straining was still progressing when the test halted. Naturally the $\sigma'_{v,c} = 70$ kPa test showed less heave, but continued creeping

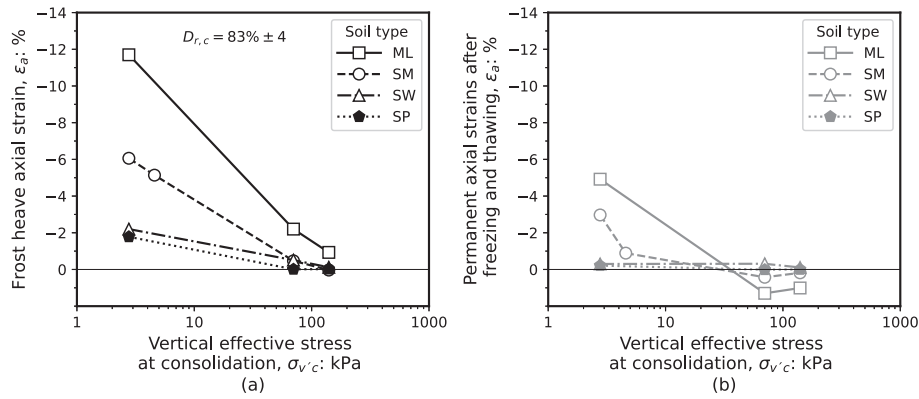


Fig. 12. Axial strains versus vertical stress: (a) at end of frost heave, and (b) permanent axial strains after a freezing-thawing cycle.

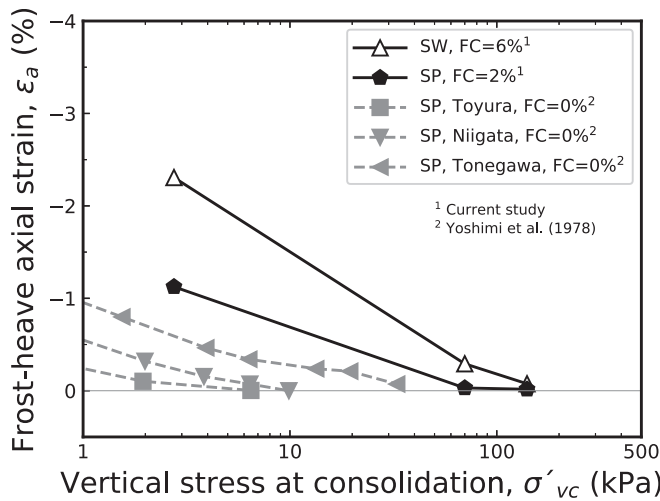


Fig. 13. Frost heave expansion vs. vertical stress at consolidation of SW and SP Øysand sand in comparison with other studies on clean SP sands.

upwards until the test stopped after 60 days. The $\sigma'_{v,c} = 140$ kPa test did not show significant frost heave.

- The SP tests (Fig. 8d) also showed significant and highly time dependent frost heaving under $\sigma'_{v,c} = 2.7$ kPa up to about 40 days, while frost heave was recorded under $\sigma'_{v,c} = 70$ and 140 kPa.

Fig. 9 shows the data discussed above replotted with respect to $\sigma'_{v,c}$. Results consistently showed that the lower FC, the lower the $\epsilon_{a,f}$. Note that the frost heave at FC = 65 % tends to reach a steady state after two days while frost heave at FC = 6 % and FC = 2 % continues to develop after >20 and 40 days. Moreover, the higher the applied $\sigma'_{v,c}$ the lower the axial strains developed during freezing (compare Fig. 9a to c). Fig. 10 presents the compressive (positive) average strains developed during thawing. The experiments show that, as expected, the higher the value of FC, the higher $\epsilon_{a,t}$. Thawing progressed rapidly, regardless of the soil tested, and was usually complete within five hours (see Fig. 10). As expected, plastic thawing strains decreased with the level of applied $\sigma'_{v,c}$. All changes in ϵ_a , and corresponding D_r , are summarized in Table 2.

The combined effects of $\sigma'_{v,c}$ and FC are summarized in Fig. 11. Frost-heave expansion increases linearly with FC, although at decreasing rates

with increasing vertical effective stress (Fig. 11a). The permanent strains developed after thawing also increase linearly with FC for all soils at the lowest vertical stress level used in this study (see Fig. 11b). Note that, for the soils tested the higher FC, the higher the ice lenses formed, hence the higher the final thawing settlements after a freezing-thawing cycle. The permanent plastic strains during thawing were the result of the observed ice lenses formation and were usually thicker in ML soils than in the sands. ML soils were deformed more by the ice, hence larger thawing strains are measured. The ice lenses formation is discussed in detail below with aid of the μ CT scans.

Fig. 12a shows how the frost-heave decreases linearly, on a semi-logarithmic plot, with increasing $\sigma'_{v,c}$. The approximate values of vertical effective stresses at which the frost-heave is subdued $\sigma'_{v,sub}$ (which is basically the effective stress at which no measurable heaving is observed) are about >70 kPa, <140 kPa, ≤ 140 kPa for the SP, SW, and SM, respectively; but frost heave was not subdued under the investigated range of $\sigma'_{v,c}$ in the ML soil. Permanent axial strains after the end of thawing are shown in Fig. 12b. The thawing strains are plastic and non-recoverable, particularly at low vertical effective stress.

Fig. 13 compares the frost-heave tests on the lower fines contents SW and SP Øysand sands with tests by Yoshimi et al. (1978) on poorly graded (SP) clean sands (FC = 0 % at $D_r = 90$ %). While the Øysand sands show similar trends, their 2 to 6 % fines contents led to significantly greater frost-heave expansion.

6. Qualitative μ CT analysis of freezing-thawing behaviour

The average axial strain measurements made with the single LVDT in the one-dimensional test apparatus could not capture the specimens' potentially complex 3D frost heave and thawing deformations. The μ CT-scans captured detailed changes in local soil fabric and allowed for qualitative visual inspection.

Fig. 14 and Fig. 15 shows the homogeneity and uniformity of the reconstituted SM and ML soils (prior freezing), respectively. The grey X-ray signal intensity values recorded during μ CT scans reflect the local soil density variations. The grey value represents the amount of X-ray attenuation (per voxel) when passing through an object. Specimen uniformity can be assessed by plotting the variations of the grey values against specimen height; as done for instance by Frost and Park (2003). The traces in Fig. 14 and Fig. 15 indicate a good uniformity distribution, with minor inhomogeneities and potential segregation leading to local voids, which are evident in the two-dimensional cross-sectional images presented in both figures. The specimen uniformity analysis was also

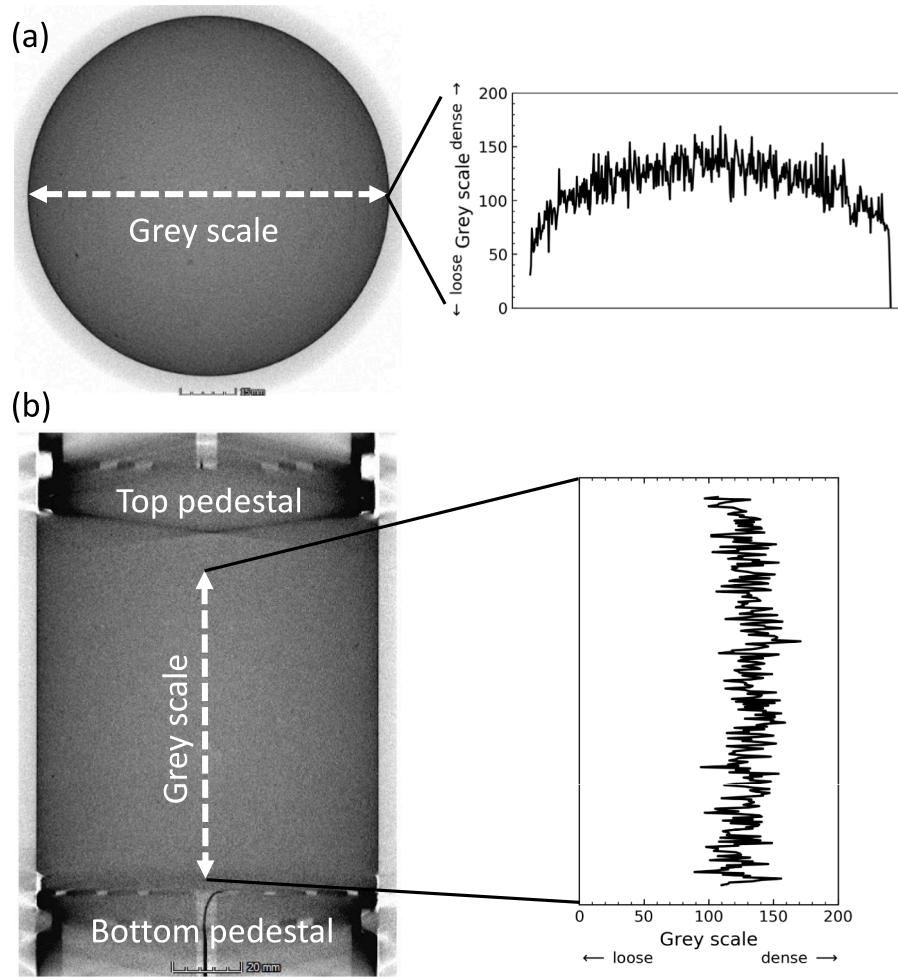


Fig. 14. μ -CT scans of dry pluviated Sandy SILT (ML) specimen inside the temperature-controlled cell before freezing: horizontal (a) and vertical (b) cross sections.

performed on SP and SW soils, with similar results.

By comparing the μ CT scans before and after a freezing-thawing cycle, it is observed that ice formation during freezing can damage the soil fabric, even in the absence of measurable frost-heave strain. Fig. 16 shown the frozen SM soil at $\sigma'_{v,c} = 140$ kPa. The LVDT measurements during this recorded no heave, though thin sub-horizontally layered voids are evident from the μ CT scans. As expected from the Konrad and Morgenstern (1984) model (sketched in Fig. 2), void formation tended to concentrate towards the (upper) sections of the specimen, which were the last to freeze, reflecting the formation of one or more ice lenses. This pattern was also clearly observed in the ML soils (see Fig. 17), where ice lenses appeared even at high effective stresses within the entire specimen, although showing a higher frequency and greater disturbance in the upper regions. Fig. 18 shows the ice lenses formation in SW soil under low stresses (at $\sigma'_{v,c} = 2.7$ kPa) where ice lens formation concentrated more distinctly towards the upper initially unfrozen zone. The lack of lenses towards the freezing boundary at the specimen base indicated that coring of frozen soil in the field should be undertaken as close as practicable to the freezing pipes where the coldest temperature

T_c is found. Although, it is also to consider that installing the freezing pipes could itself disturb the soil around them.

7. Conclusions and practical implications

The study described led to the following six main conclusions:

1. The average vertical strains developed by the Øysand soils on freezing increased systematically with fines content and reduced with applied vertical stress.
2. Freeze-thaw cycles lead to little overall permanent deformation in clean sands and average strains that increased with fines content.
3. Minimum vertical effective stress levels were established for the Øysand soils above which little or no 1-D frost-heave average axial straining occurred.
4. The experiments indicate the minimum depths at which ground freezing could be applied to aid sampling without causing heaving strains in situ were approximately 25 m, 12 m, 10 m and 7 m respectively for the ML, SM, SW and SP soils encountered.

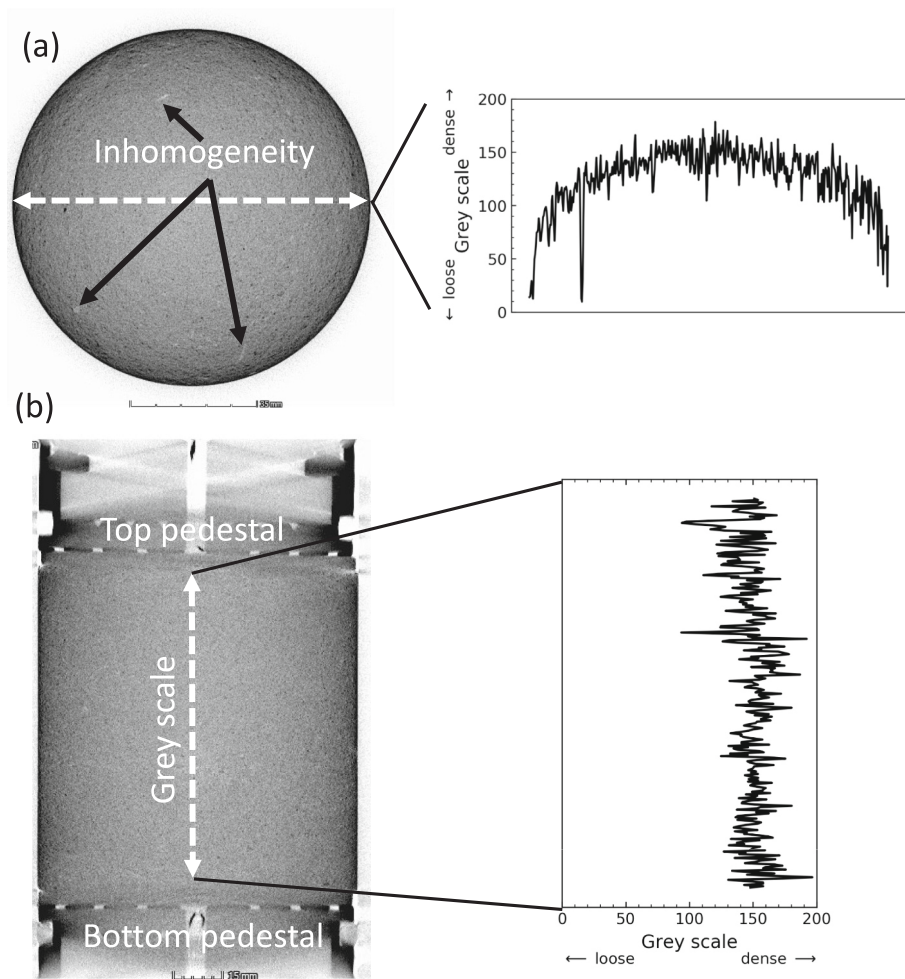


Fig. 15. μ-CT scans of of dry pluviated Silty SAND (SM) specimen inside the temperature-controlled cell before freezing: horizontal (a) and vertical (b) cross sections.

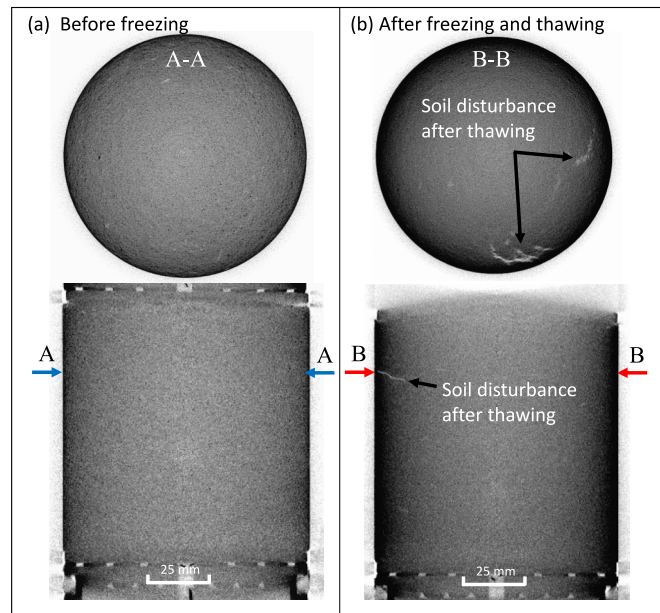


Fig. 16. μCT-scans of SM at $\sigma'_{v,c} = 140$ kPa: (a) before freezing and (b) after a cycle of freezing and thawing.

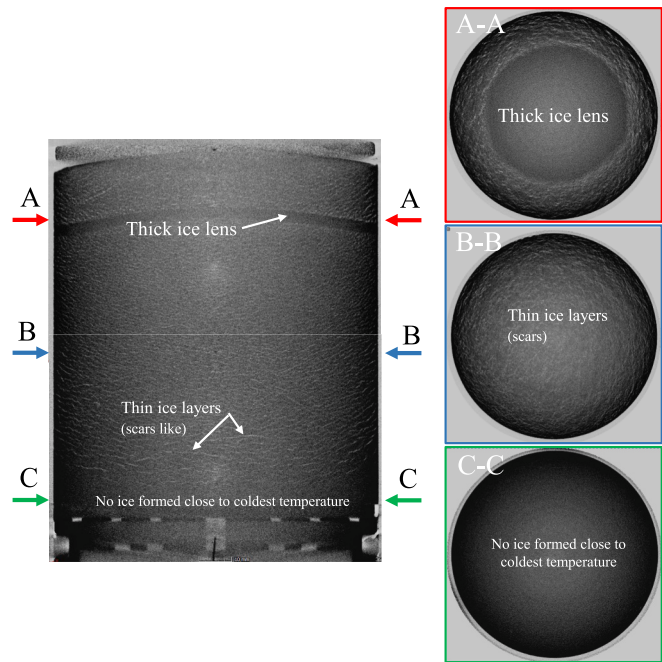


Fig. 17. μCT-scan cross sections of ML specimens tested at 140 kPa after a freezing-thawing cycle.

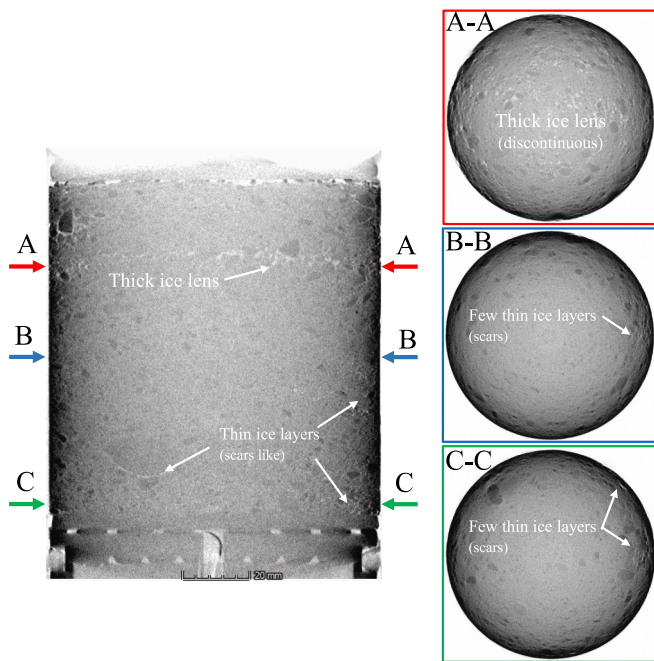


Fig. 18. μ CT-scan cross sections of SW specimens tested at 2.7 kPa after a freezing-thawing cycle.

- Careful inspection of scanned μ -CT images taken before and after specimens underwent freeze-thaw cycles identified the soil fabric changes and showed that disturbance can occur even in the absence of measured frost-heave straining.
- Disturbance due to ice lens formation develops most clearly close to the warmest isotherm, at points distant from the freezing boundary.

The experiments indicated that in situ ground freezing could be effective to aid low-disturbance sampling of SP and SW soils at depths where the in situ vertical effective stresses exceed about 100 kPa. The results also suggest that sampling should take place near to the installed ground freezing pipes. However, ground freezing assisted sampling appears less likely to be effective for the ML and SM soils in layers where the in situ vertical effective stress in the field falls below the levels required to suppress plastic and non-reversible straining during freezing and thawing. The experiments also offer useful information for engineers undertaking frost-heave susceptibility assessments in soils with similar compositions for other geotechnical applications, including retaining walls, foundations, highways and rail lines.

CRediT authorship contribution statement

V. Santiago Quinteros Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **J. Antonio H. Carraro**: Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Jean-Sebastien L'Heureux**: Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization. **Richard J. Jardine**: Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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