Effects of Temperature on Volumetric Behavior of Soil Subjected to Freezing-Thawing Cycles

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ABSTRACT

This paper presents an experimental investigation related to the effect of Freezing-Thawing (F-T) cycles on the volumetric behavior of soils, with particular focus on the impact of the range of freezing temperatures on soils response impact. A reconstituted specimen made up from a commercial silt was subjected to F-T cycles in an 1D cell manufactured in a 3D-printer. The soil specimen was fully saturated, and the test was conducted under open system conditions inside an environmental chamber. Volume changes were recorded using a Linear Variable Differential Transformer (LVDT) during cyclic F-T. The test results show that the impact of the range of the freezing temperature is only relevant in the higher range of freezing temperatures (i.e. near the freezing point), and it tends to reduce significantly as the minimum temperature reduces. The study also shows that stress-history of the soil has a significant influence on the volumetric behavior soils subjected to F-T cycles.

INTRODUCTION

Seasonal frozen soils dominate approximately 55% of the total earth's surface land (Zhang et al., 2003). This area corresponds approximately to 55 million km^2. In those regions, a good understanding of the behavior of frozen soils is critical for a safe and economical design of new civil infrastructure and for assessing the condition of existing structures. Furthermore, with the discovery of fossil fuels in recent years, for example petroleum and gas hydrates near the Arctic Circle as well as permafrost regions worldwide, frozen soils will likely become a topic of central interest.

As a result of their wide distribution, frozen soils are of importance, and problems resulting from frozen soils, especially soils subjected to cyclic freezing-thawing process are becoming more significant constraints in many fields (i.e., engineering construction, waste disposal and energy exploitation). This is because engineering properties of the soils such as strength, stiffness, coefficient of permeability, and mechanical behavior change drastically with changes in temperature and freezing-thawing cycles. These property changes give rise to many engineering practical problems, bringing significant financial losses and safety problems, such as distress of foundations due to thawing, leading to cracking of the super structure; railroad distortion due to heaving of the soil; road surface damage due to thaw weakening etc. In addition, the noticeable recent changes in climate worldwide, the increasing energy resource exploitation demand in frozen ground, and the promising application of artificial ground freezing technique for ground improvement, have enhanced the interest in the study of frozen soils.

It has been shown that, when the temperature falls below the water freezing point, not all the pore-water present in the soil is converted into ice (Taber. 1930). There is an amount of unfrozen water that attributed to capillary phenomena remains in liquid phase (see Figure 1). The amount of unfrozen water content plays a critical role in evaluating the volumetric behavior of frozen soil because it indicates how much water has been changed from water to ice (i.e., volume expansion from water to ice is around 9%).

Different experimental techniques have been proposed to determine the amount of unfrozen water in soils, e.g., calorimeter method (William, 1964), nuclear magnetic resonance (Tice et al., 1982), differential scanning calorimetry (Kanitha and Reid, 2004), electrical conductivity (Mao et al., 2018). In this paper, unfrozen water content was measured through electrical conductivity method. For the soil we utilized in the research, the unfrozen water content changes as a result of different freezing temperatures were measured at the beginning, because it is critical when evaluating volumetric behavior of cyclic F-T tests under different F-T temperature ranges.

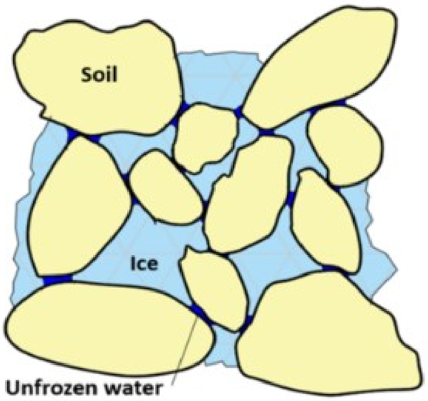


Figure 1 Schematic representation of frozen soil

The experimental study of the mechanical behavior of frozen soils has been generally based on reconstituted specimens (e.g., Sayles 1974; Parameswaran 1980; Parameswaran and Jones 1981, Arenson et al. 2004; Chen et al. 2020). This is because gathering frozen undisturbed samples from the field is challenging and expensive. In some works, undisturbed soil samples were retrieved in-situ and were frozen in the lab before testing them (e.g., Cui et al. 2014; Tang et al. 2018; Zhou et al. 2018). Only a few studies have been based on natural frozen samples (e.g., Shastri et al., 2022). In terms of cyclic F-T tests, most of the experimental investigations are based on studying the behavior of specimens that were already subjected to F-T cycles (either in the lab or in the field) and comparing their responses against untreated soils. Konrad, 1989 reported that over-consolidated clays tend to expand when subjected to F-T cycles and that this tendency is more notorious as the Over Consolidation Ratio (*OCR*) increases. Viklander, 1998 studied the permeability and volume changes of Normally Consolidated (*NC*) and Over Consolidated (*OC*) soils subjected to F-T cycles. The permeability of *NC* samples decreases because of the tendency of the soil to contract during F-T cycles. An opposite behavior was observed in *OC* specimens. Both, *OC* and *NC* samples tend to a residual void ratio after a number of cycles. Similar behavior was observed in silty soil studied by Qi et al., 2008 and Zhou et al., 2017. Eigenbrod, 1996 found that fine-grained NC soils tend to contract during F-T cycles. Eigenbrod et al., 1996 reported that no net volume changes were observed after F-T cycles in *NC* samples with water content close to the plastic limit. Other studies related to soils subjected to F-T cycles are focused on dynamic response, long-term cyclic loading, rheological properties, resilient modulus, and influence of salt content and salt type.

However, the current knowledge on volumetric behavior of frozen soils subjected to F-T cycles under different F-T temperature ranges with considerations of loading history is quite limited. This paper introduced an experimental campaign focused on investigating such behavior by performing a series of cyclic F-T tests in an environmental chamber. The unfrozen water content under different freezing temperatures was also measured and a detailed discussion on how F-T temperature range affected soil volumetric behavior was also presented.

TEST MATERIAL

Silt designated as SIL-CO-SIL 75 from the U.S. Silica Company was adopted for this experiment. This silt was white in color and had a very low plasticity. Routine geotechnical tests were conducted to determine the basic properties of this soil (Table 1). The liquid limit of the sample was determined to be 25.3%. This material did not exhibit a plastic behavior, for example the plastic limit could not be determined, therefore the soil was considered as non-plastic (NP). The adopted water content was around 1.2 times the liquid limit and was set equal to 30%. The specific gravity of this soil was 2.65. The initial saturation degree was 100% and initial void ratio was 0.8.

Table 1. Summary of the soil properties

Property	Value
Liquid Limit, LL (%)	25.30
Specific Gravity, G_S	2.65
Dry Density (kg/m^3)	1350
Water content (%)	30
Initial Void Ratio, e_0	0.80
Degree of Saturation, S_r (%)	100

EXPERIMENTAL SETUP

A high-quality 3D printer was used to manufacture the one-dimensional cell adopted in this research. It consists of the following main components: a base pedestal; an inner-ring (to house the soil); a plunger (to apply the vertical stress); an outer-ring (to provide a seal all around and to support the plunger); a LVDT (linear variable differential transformer); and a mount (which assembles all the components together). Figure 2a_ and 2b show the adopted setup and the setup inside the chamber. O-Ring seals between outer-ring and pedestal were included to ensure a watertight setup. The pedestal was designed with drainage at the bottom connected to a source of free water to produce an open system and allow free drainage. The inner ring can host soil specimens 39mm height and 39mm diameter. Porous stones were placed at the bottom and top of the samples. The vertical load was applied as a dead load through the plunger.

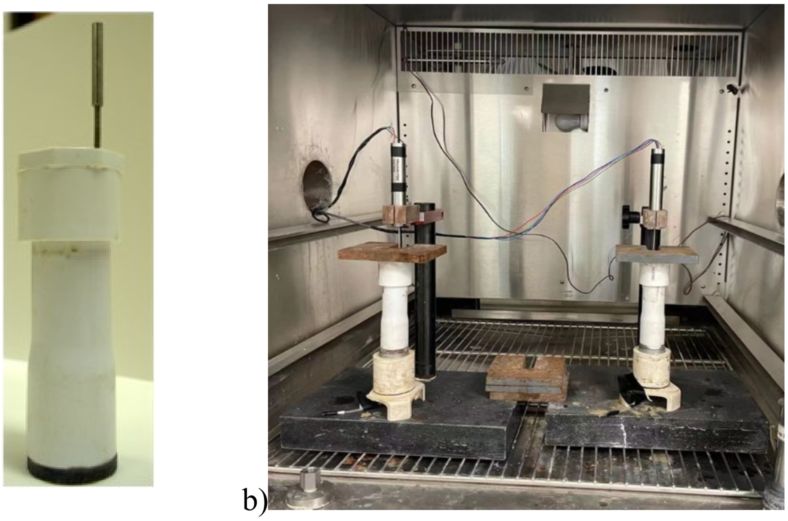

a) b)

Figure 2. a) 1-D cell adopted in the experiments b) 1-D cells inside the CSZ chamber.

The LVDT (SE-750-500) attached to the top of the plunger tracked the vertical displacements during the test. This LVDT is specially designed to operate under freezing temperature (-20°C to 70°C). The F-T cycles were conducted inside a CSZ 0.45m^3 (16ft^3) environmental chamber capable of temperature (-40°C to 179°C) and relative humidity (5% to 98%) computer-controlled cycling (Figure 3a)). The temperature inside chamber was also measured using an built in thermocouple. The set-up was calibrated for the range of temperature contemplated in this research.

The oven-dried silt was mixed with distilled water at the target water content (i.e. ~w=30%) and the mixtures were left inside hermetic plastic bags for 24 hours to attain homogenized specimens. All the samples were prepared inside the cell in slurry state. A light tapping was applied to remove any possible air-bubble. LandMapper ERM-02 (Figure 3b) was selected in this preliminary research to measure the electrical conductivity (*EC)* of the silty soil. It is a four-electrode portable device, easy to calibrate and use.

a) **b)**

Figure 3 Test equipment a) Environmental chamber; b) LandMapper ERM-02

UNFROZEN WATER CONTENT MEASUREMENTS

To estimate the amount of the unfrozen water retained at different freezing temperature electrical conductivity method was used. The LandMapper ERM-02 device was adopted in this study (see Figure 3b) following the method and procedure reported in Mao et al., (2018. A large amount of silt was mixed with distilled water to reach a water content of 30% (slurry sample) in a large glass beaker as discussed before, and the beaker was then sealed with a plastic bag for a 24 h settlement. Liquid on top of the sediment will be used as the interstitial liquid for this method. Thermometer probes and the LandMapper ERM-02 were placed in the liquid and then glass beaker with liquid was placed in the environmental chamber. Reading of temperatures as well as electrical conductivity were taken outside of the chamber by thermometer and LandMapper ERM-02 separately. Chamber temperature was controlled from positive to negative to get a curve relating EC and temperature values of the interstitial liquid alone. Additional soil sample with water content of 30% was prepared and move it into the mold as discussed before. Both the thermometer probe and LandMapper ERM-02 probe were inserted into the middle of the soil sample, and then whole set-up was placed into the environmental chamber. Reading of temperatures as well as electrical conductivity were taken outside of the chamber by thermometer and LandMapper ERM-02 separately. Chamber temperature was controlled from positive to negative to get a curve relating EC and temperature values of the soil sample.

The saturation degree of unfrozen water, S_{luw}, was estimated based on Archie's law: $S_{luw} = \frac{EC_s \times n^{-p} \times S_l{}^{-q}}{EC_w}$; where EC_s and EC_w are the electrical conductivities of the frozen soil and interstitial liquid, respectively, n is the porosity, p is an exponent related to soil structure, and q is an exponent associated with S_l (S_l=1 in this case). The following values have been suggested for the parameters involved in the equation above: q~2.0 and 1.4<p< 2.0.

The EC of soil was shown in Figure 4a), the freezing point of the interstitial liquid was around 0°C and the EC of frozen soil decreased sharply at the very beginning (i.e., 0 to -2°C) when temperature decreases negatively, same thing happened with S_{luw}. But, for temperature below -2°C, S_{luw} remains almost stable and very low (see Figure 4b)). This appears to be because for this soil, and the existing experimental conditions, virtually all the water was frozen after the 0 to -2°C range freezing process.

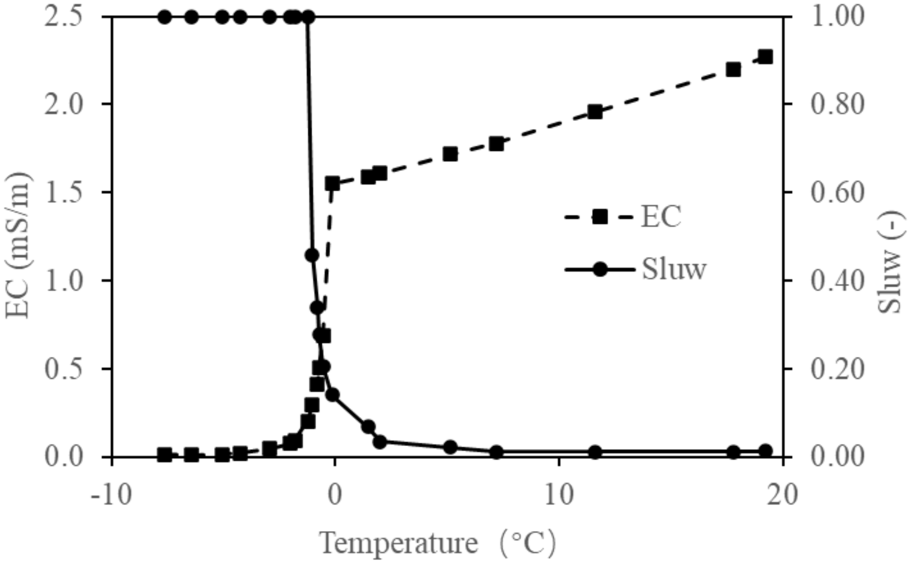
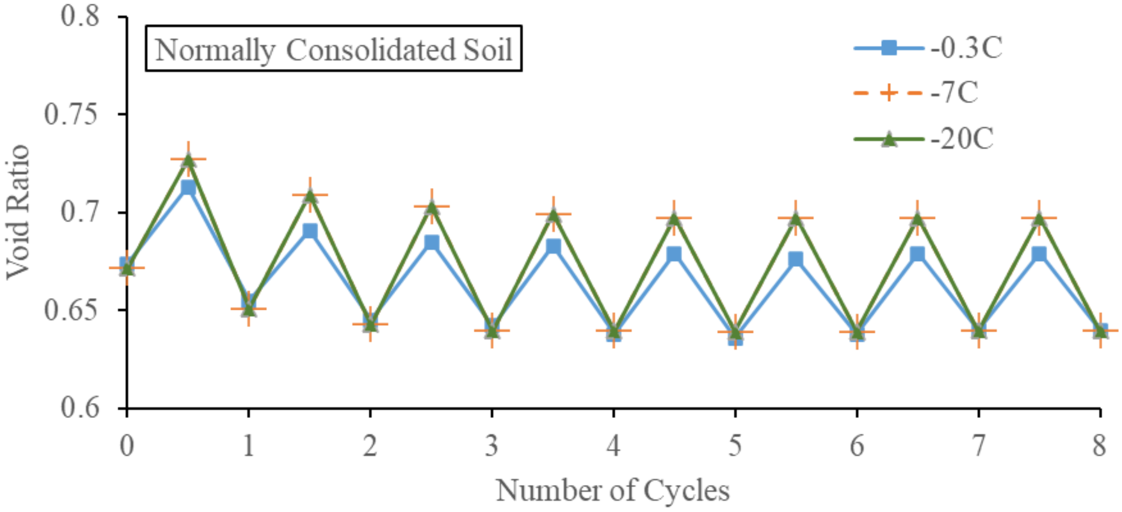


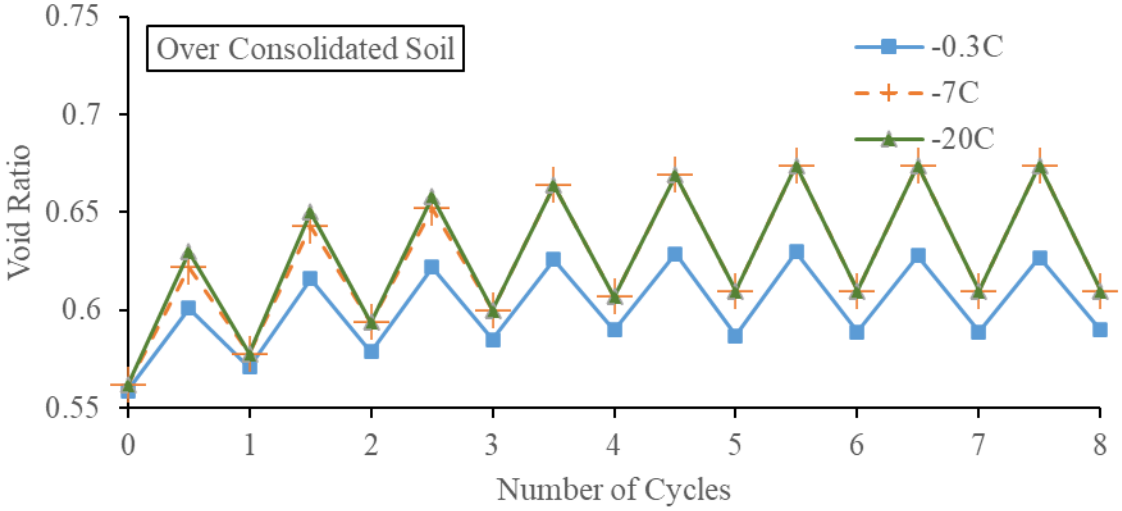
Figure 4. EC and Unfrozen water retention curve

CYCLIC TESTS UNDER DIFFERENT F-T TEMPERATURE RANGE

Six tests in three groups were conducted to investigate the potential effects of the temperature range on soils volume change subjected to F-T cycles. Temperature variations between -0.3°C and 5°C were applied to Normally Consolidated (*NC)* specimens under σ'_v=10kPa and Over Consolidated (*OC)* samples under the same σ'_v but previously loaded up to σ'_v=500kPa. A similar protocol was followed to the other two groups of specimens subjected to temperature changes between [-7°C to 5°C] and [-20°C to 5°C]. In all the cases a maximum of 8 F-T cycles were investigated. In all the tests the volume change was stable after the 6 cycles. The primary results are presented in Figure 5. It can be observed that for the two states considered here (i.e., *NC* and *OC*), *NC* soil tended to contract while *OC* soil tended to expand. The contraction amount for these three *NC* groups was almost the same, but for *OC* soil the range [-0.3°C to 5°C] induced less final expansion than the other F-T temperature two ranges. Furthermore, the sequence [-0.3°C to 5°C] induced less volume changes during F-T cycles than the other two temperature ranges, also there were practically no differences between the series [-7°C to 5°C] and [-20°C and 5°C]. According to unfrozen water content measurements, this behavior could be anticipated because unfrozen water content was almost the same for sample under -7°C and -20°C.



a)



b)

Figure 5 Effect of temperature range during F-T cycles on soil behavior a) *NC* soil; b) *OC* soil

DISCUSSION AND CONCLUSION

Through this experimental study, a better understanding of the volumetric behavior of frozen soils subjected to different loading histories, and different temperature ranges during F-T cycles was achieved. As for the effect of the temperature range on soils subjected to F-T cycles, a marked difference in terms of volumetric behavior was observed when comparing the range [-0.3°C to 5°C] and [-7°C to 5°C]. However, almost no difference was observed in the volumetric response of the samples when comparing the ranges [-7°C to 5°C] and [-20°C to 5°C]. This behavior can be explained when inspecting the unfrozen-water content retention curve. It is observed that at the very beginning of the cooling stage (i.e., close to freezing point) the amount of unfrozen water decreased sharply, but at lower temperatures the S_{luw} remained almost stable and very low. It was observed that for this particular soil, almost all the water is in the ice form when the temperature is below -2°C. This behavior explained why little or no noticeable differences in terms of volume changes are observed when comparing the response of sample during F-T cycles at the low temperature ranges (i.e., [-7°C to 5°C] against [-20°C to 5°C]).

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