Undrained Shear Strength of Frozen Unsaturated Silts

Anshu Abhinav[1], and *Tugce* Baser[2*]

[1] Graduate Research Assistant, University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, 205 N Mathews Urbana, IL 61801
[2] Assistant Professor, University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, 205 N Mathews Urbana, IL 61801

Abstract. This study focuses on investigation of the undrained shear strength of unsaturated frozen silts prepared at varying initial thermal and hydraulic conditions. The initial degree of saturation controls ice and unfrozen water contents at temperatures below depression point. The strength properties of frozen soils are highly influenced by ice and water contents which is highly coupled with thermal state of the soils. To evaluate the strength properties of frozen silts, a series of direct simple shear experiments were performed using Bonny silt prepared at different initial degrees of saturation under monotonic shear loading. Compacted silt samples at varying degrees of saturation were subjected to artificial freezing before shear loading and stress-strain curves were recorded during loading. Identical samples were prepared and sheared at room temperatures for comparison. The stress-strain behavior of frozen silts was observed to be significantly different than those of obtained at room temperatures where on an average the shear strength of the saturated frozen soils was higher by 150% in comparison to the shear strength of the same soil in saturated unfrozen condition. The undrained shear strengths for frozen soils were also observed to be affected by initial degree of saturation where the strength was observed to increase by 142 % when the initial degree of saturation was increased from 0.51 to 1.00. The results obtained from this study will be used in ongoing investigations of capacity of deep foundations in warming permafrost.

1 Introduction

The global warming in the previous century has led to a rise in subsurface temperatures in the permafrost regions (i.e., Arctic) [1-3]. Thawing of permafrost due to rising temperatures can cause severe damage to infrastructures due to a reduction in the strength of soil, causing mass movements in the form of landslides and forming thermokarsts [4-7]. To develop sustainable infrastructures in the Arctic, it is imperative to quantify the strength of frozen soil and estimate the reduction in strength of the subsurface due to thawing. Several researchers have investigated the strength behavior of frozen soil however, a detailed study on the effect of initial degree of saturation on the shear strength and reduction in strength due to thawing is limited. Therefore, this study aims to systematically quantify the effect of initial degree of saturation on the frozen strength of soil and the expected reduction in strength due to thawing. Direct Simple Shear (DSS) [8] tests were performed on frozen and unfrozen soil samples where the samples were constrained to distort in shear without forming a shear plane. Samples in saturated and unsaturated conditions were monotonically sheared and the stress-strain behavior was characterized.

2 Background

Many researchers have investigated the shear strength of frozen soils and its dependency on temperature, ice content, density, strain rate, and confining pressure [9-11]. Temperature has a significant effect on the shear strength of frozen soils where the decrease in temperature below the freezing point can exponentially increase the shear strength of the soil [12, 13]. Some researchers have also observed that the variation of shear strength is linear with the decrease in temperature [14, 15]. Triaxial tests on dense sands in frozen and unfrozen conditions have revealed that the increase in strength upon freezing is caused due to generation of internal confinement or apparent cohesion due to the presence of pore ice [16]. Thus, both components including tensile stresses and the shear strength of the ice matrix contribute towards the shear strength of frozen soils [17]. The ice content significantly affects the strength behavior of frozen soil as observed from the unconfined compressive strength tests comparing the strength of pure ice and ice specimens with increasing soil content [18]. The first mechanism is ice strengthening where the strength of ice increases due to altered structure, deformational constraints, or different stress states upon increasing the soil content. As the soil fraction increases, strength increases due to the synergistic interaction between soil and ice where both

* Corresponding author: tbaser@illinois.edu

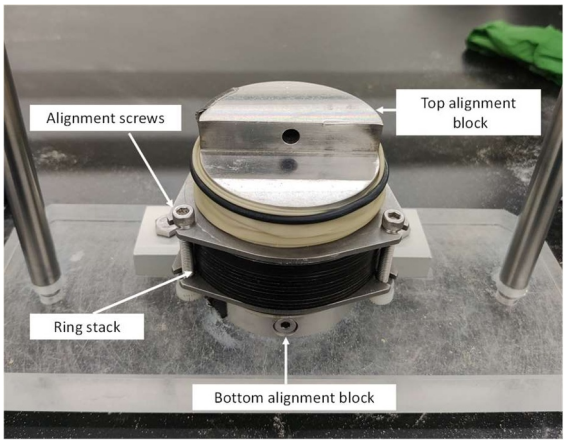
components carry a portion of the applied load. As the soil fraction increases, the sample becomes dense and tends to dilate under applied shear stress this causes tension in the pore ice which passively increases the apparent confining pressure. For a constant dry density, the ice content below freezing temperatures increases with the increase in initial degree of saturation which increases the shear strength of the frozen soil [19, 20]. The shear strength also depends on the applied strain rate where the shear strength is observed to increase exponentially with the increase in strain rate [13]. The value of this exponent relating the shear strength and the rate of strain is dependent on the density of the specimen [21]. The shear strength of the frozen soil is also dependent on the confining pressure during the test [22]. With the increase in confining pressure, the strength of the soil increases until a critical confining pressure is reached. If the confining pressure is increased further, the strength of the soil is observed to be decreasing due to pressure melting of pore ice, growth of microcracks and particle size breakdown [22].

3 Experiment setup and approach

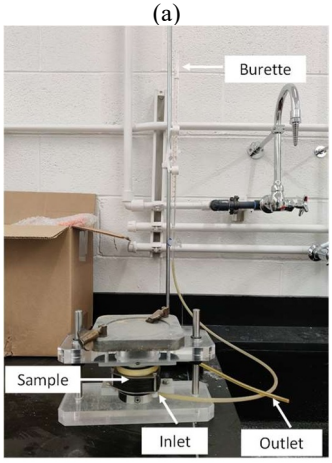
Direct shear test is the most used test for soils to characterize the strength parameters to obtain friction angle and cohesion. However, this method has several limitations including fixation of the failure surface which might not be the weakest plane and stress concentration at the edges. The DSS test overcomes this limitation by uniform deformation of soils in a direction perpendicular to the normal stress without forming a shear surface nor a change in cross sectional area of the specimen. The DSS test is used to simulate the mode of shear along horizontal or gently inclined portions of the slip surface [23].

3.1 Sample preparation

To investigate the strength properties of frozen soils, a series of DSS tests were performed using Bonny silt. Bonny silt is classified as a low plasticity silt according to the Unified Soil Classification System. The soil was passed through #10 sieve and then oven-dried for 24 hours at a temperature of 100°C. The oven-dried soil was mixed with amount of deionized water to attain the desired degree of saturation. After thorough mixing, the soil was sealed in bags to allow moisture equilibration for at least 24 hours in the moisture room. The soil was then compacted in the cylindrical mould to a dry density of 1400 kg/m^3 and a void ratio of 0.47 with a sample diameter of 67.3 mm and height of 18 mm. The sample was prepared using under compaction method [24] in two layers of equal thicknesses. The sample along with the ring stack is shown in Figure 1(a). For the experiments with initially saturated soil, the specimen was compacted as above and was saturated using a standpipe as shown in Figure 1(b). The deionized water from the standpipe entered the soil sample through the bottom alignment block, permeate through the soil sample, and allowed to escape through the top alignment block. The constant flow through the specimen was maintained for 24 hours to completely saturate the soil from bottom to the top. The sample was then consolidated to the vertical stress desired during shearing in the following steps: 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, and 200 kPa. After consolidation, the sample was monotonically sheared at the desired constant normal stress and a shearing rate of 0.1 mm/min to a maximum shear strain of 30 percent. In case of frozen soil specimens, the soil sample was prepared and consolidated using the same procedure as it was for the soils in the room temperature to attain the same void ratio. The soil samples were frozen inside the refrigerator to a temperature of -30°C before shearing under ambient temperature conditions. After shearing, the samples were extruded, and the water content was measured by oven drying method. The degree of saturation was confirmed to be greater than 0.9 for the soil sample to be considered as saturated.



(a)



(b)

Fig. 1. Experiment setup: (a) compacted soil sample with ring stack and alignment blocks and (b) saturation setup for initially saturated specimens.

3.2 Experiment Matrix

Experiments were performed to better understand the thermal and hydraulic parameters affecting the shear strength of silty soils. Two different degrees of

saturation were used to investigate its impact on the strength behavior. The experiments were performed at three different normal stresses to quantify the effect of depth from the surface. The experiment matrix for DSS is shown in Table 1.

Table 1. Matrix for experiments

Dry density (kg/m^3)	Void ratio (m^3/m^3)	S_r (m^3/m^3)	Normal Stress (kPa)	Thermal state
1400	0.47	0.51, saturated	50, 100, 200	Unfrozen
1400	0.47	0.51, saturated	50, 100, 200	Frozen

4 Results and discussions

To investigate the strength behavior of soils in different initial conditions, the soil samples were monotonically sheared with a rate of 0.1 mm/min under a constant normal stress condition. In the case of unfrozen soils, strain hardening behavior was apparent from the stress-strain curves, and the soil was assumed to fail at a shear strain of 20% according to the ASTM standards [25]. The strength and change in sample height of the specimen at failure was reported at a shear strain of 20 %. In case of frozen soils, the failure was assumed at the initial peak observed at shear strain values approximately around 3%.

4.1 Shear stress vs shear strain behavior

The stress-strain curves obtained from the experiments are shown in Figure 2(a) through 2(c). The comparison between the stress-strain behavior for the normal stress of 50 kPa is shown in Figure 2(a) for different degrees of saturation and initial thermal states. The unfrozen soil sample having a degree of saturation of 0.51 exhibited a shear strength of 38 kPa whereas, the frozen specimen exhibited a shear strength of 38.6 kPa. In the case of saturated sample, the shear strength was determined to be 27 kPa in unfrozen condition. However, frozen saturated soil sample exhibited significantly higher shear strength with a value of 128 kPa. The stress-strain curves from the experiments where a normal stress of 100 kPa was applied are shown in Figure 2(b). The shear strength for the soil prepared at an initial degree of saturation of 0.51 was determined to be 61 kPa in unfrozen condition and this value was 42 kPa in frozen condition. However, in case of saturated soil, the shear strength was determined to be 56 kPa and 96 kPa for initially unfrozen and frozen conditions, respectively. In Figure 2(c), the stress-strain curves for different initial conditions and thermal states at a normal stress of 200 kPa were compared. For silts having an initial degree of saturation of 0.51, the shear strength was obtained as 64 kPa and 100 kPa under frozen and unfrozen conditions, respectively. For the saturated samples tested under 200 kPa, these values were 93 kPa and 105 kPa for unfrozen and frozen conditions, respectively.

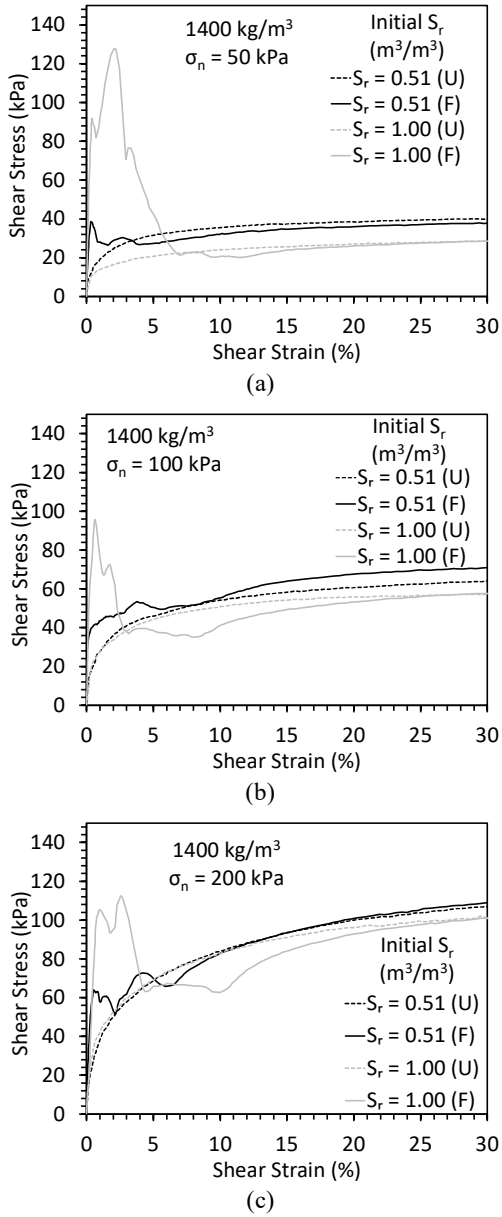


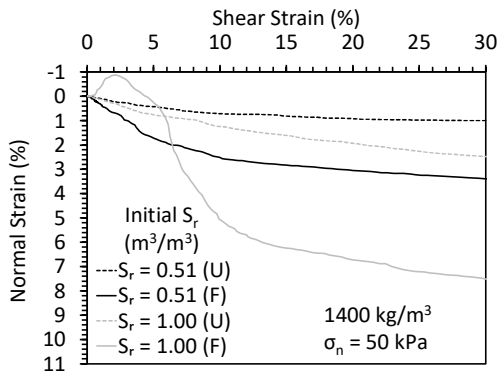
Fig. 2. Stress-strain behavior of soil specimens at a normal stress of: (a) 50 kPa; (b) 100 kPa; (c) 200 kPa.

The soil samples showed a strain hardening behavior under unfrozen conditions, because the shear stress increased with the increasing shear strains during loading. This behavior is attributed to an increase in the density of the sample. More specifically, the unfrozen soil samples showed contractive behavior under constant normal stress, and this was an indication of increasing density during the shearing process as can be seen in Figures 3(a) through 3(c). The stress-strain curves for the frozen soils reached a peak shear stress value at relatively low strain values followed by slower decrease merging with the stress strain curves of the unfrozen soil specimens at higher strain values. The higher peak strengths can be explained by shearing of ice in the frozen soil at early stages of the experiments. The shear strength in frozen condition was also observed

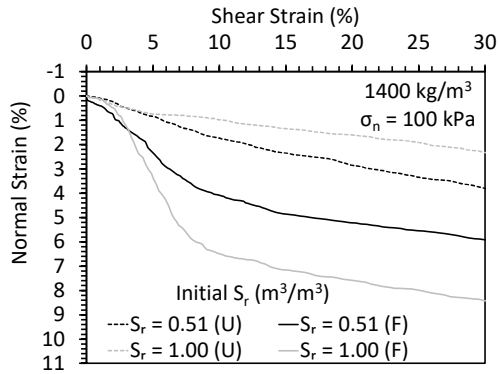
to be increasing with the increase in degree of saturation due relatively higher ice contents resulting in more substantial reduction in shear strength due to thawing. Although the shear strength of soil having an initial degree of saturation of 0.51 observed to have higher shear strength relative to those obtained for the unfrozen conditions, the unfrozen samples failed at higher strain values (i.e., 20%) whereas the frozen soil generally failed at strains approximately around 3%. Thus, higher shear strains are expected if an unsaturated frozen soil thaws under the same shear stress.

4.2 Normal strain vs shear strain behavior

During the shearing process, the normal stress on the specimen was regulated to be constant and the vertical displacement was measured. The variation of normal strain with the shear strain for all silt specimens are shown in Figure 3(a) through 3(c). Under a normal stress of 50 kPa, it can be observed from Figure 3(a) that the unfrozen specimens having a degree of saturation of 0.51 and 1.00 exhibited a contractive behavior with a total normal strain of 0.92 % and 1.95 % respectively. The frozen sample having a degree of saturation of 0.51 also showed a similar behavior where the normal strain at failure was 0.09 %. However, the frozen saturated sample exhibited a completely different behavior, where the specimen was dilatant at lower shear strains. The maximum dilation in the form of normal strain value was 0.88 % at a shear strain value of 2.04 %. It can be observed from Figure 3(b) that all specimens exhibited a contractive behavior when monotonically sheared under a normal stress of 100 kPa. The samples having a degree of saturation of 0.51 in initially frozen and unfrozen conditions experienced normal strains of 0.37 % and 2.87 % respectively. Whereas, for saturated samples the normal strain was observed to be 0.08 % and 1.61 % for initially frozen and unfrozen conditions respectively. In Figure 3(c), the shear strain vs normal strain for different initial conditions at a normal stress of 200 kPa were compared. The soil samples having initial degree of saturation of 0.51 exhibited a contractive normal strain of 4.07 % and 0.11 % for frozen and unfrozen conditions, respectively. For the saturated specimens, the normal strain measured was 3.22 % and 0.41 % for unfrozen and frozen specimens respectively.



(a)



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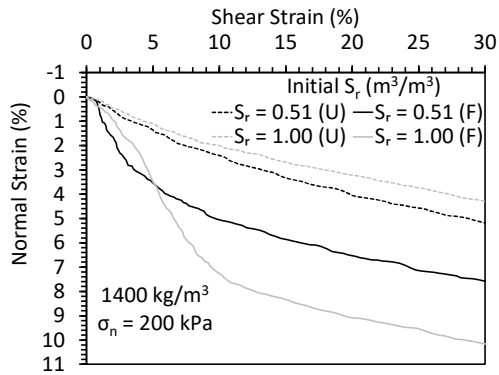

(c)

Fig. 3. Effect of shear strain on the normal strain of soil specimens at a normal stress of: (a) 50 kPa; (b) 100 kPa; (c) 200 kPa.

4.3 Shear strength vs normal stress

The shear strengths of the bonny silt at a density of 1400 kg/m^3 and different initial conditions and normal stresses is plotted in Figure 4. The shear strength of the saturated frozen soil was observed to be much higher compared to specimens with other degrees of saturation or thermal conditions. In saturated frozen condition, the shear strength was observed to be highest for the normal stress of 50 kPa due to dilation during shearing. On comparison of Figure 2(a) and Figure 3(a), it can be concluded that the soil sample exhibited the peak strength at a shear strain of 2.04 %, where the sample had peak value of dilation. The shear strength at 100 kPa and 200 kPa normal stresses were observed to be comparable to each other and no dilation was observed in the samples. In case, of unsaturated frozen soil, the shear strength increased with the increase in confining pressure as shown in Figure 4. For unfrozen soil samples, the strength was observed to be increasing linearly with the increase in normal stress. The strength of the soils is represented in terms of Mohr-Coulomb strength parameters. For unfrozen soils, the strength was represented in terms of friction angle and cohesion intercept however, for frozen conditions, the strength was represented only in terms of average ice strength. For the saturated sample under unfrozen condition, the friction angle and cohesion intercept were observed to be 25° and 5.4 kPa respectively. In case of unsaturated

soil, the friction angle was measured to be 22° whereas, the cohesion intercept was 18.7 kPa. For the unsaturated frozen soil, the average shear strength was measured to be 48.0 kPa. However, for the saturated frozen soil, the average strength was observed to have a value of 109 kPa. Thus, it can be clearly observed that the contribution of ice towards the strength of the frozen soil is highly dependent on the ice content which is higher for higher initial degree of saturation.

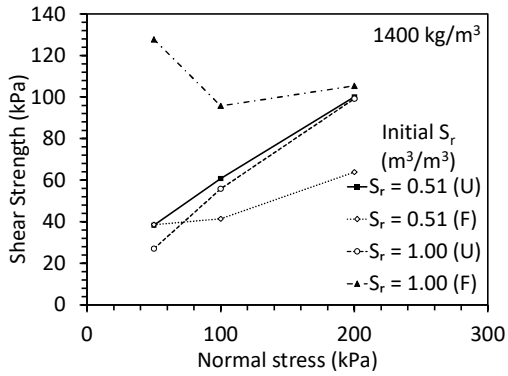

Fig. 4. Shear strength of the soil at different initial conditions and normal stresses.

5 Conclusions

To quantify the reduction in shear strength of frozen soil upon thawing at different degrees of saturation, a series of direct simple shear tests were performed with inorganic silt. The samples were consolidated under required normal stresses and monotonically sheared under a shear rate of 0.1 mm/min. During the shearing process, the normal stress was kept constant, and the vertical strains were measured. The main conclusions drawn from this study are as follows:

- The frozen soils showed strain hardening behavior and were assumed to fail at a strain of 20 %. However, frozen soils showed a peak strength behavior at a shear strain lower than 3 %.
- On an average, the shear strengths of frozen saturated soils were higher by 150 % when compared to the shear strengths of soil in unfrozen and saturated condition.
- On an average, the shear strengths of frozen unsaturated soils were lower by 22 % in comparison to soil in unsaturated unfrozen condition. However, the strain required for failure of unfrozen soil was 7 times more than that of frozen soil.
- The shear strength of saturated frozen soil at a normal stress of 50 kPa was observed to be 27 % higher than shear strengths at 100 and 200 kPa. The higher strength at lower normal stress was due to dilation which was suppressed at higher normal stresses.
- On an average, the shear strength of frozen soil increased by 142 % when the initial degree of saturation was increased from 0.51 to 1.00.

The results presented in this work is specific to inorganic silts. Ongoing research will focus on comparing the frozen and unfrozen stress-strain behavior of different types of soils under different initial degrees of saturation. The results from this study will be useful in developing meaningful relations to estimate the reduction in strength of soil due to permafrost thaw.

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