Dewatering induced by frost heave in a closed system

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ABSTRACT
The formation and growth of segregated lenses during frost heaving has long been demonstrated to lead to redistribution of soil pore water and may play an important role in the freeze-thaw dewatering and consolidation process. The study examines the frost heave process of a closed soil system, i.e. with no external water source. Two closed system step-freezing frost heave tests were conducted on an initially saturated, moderately frost susceptible sandy-silt. The total surface heave, vertical temperature profile, and basal pore pressure in the unfrozen soil were recorded throughout the test along with the final water content in the unfrozen zone. It was observed that the growth of ice lenses lead to substantial decreases in the pore pressure and ultimately dewatering in the unfrozen soil. Furthermore, the lack of external water source was not observed to substantially impede the frost heave rate for the duration examined.

RÉSUMÉ
Il a été démontré que la formation et la croissance de lentilles de glace durant le gel mène à la redistribution de l'eau interstitielle des pores et peut jouer un rôle important dans les procédés de drainage et de consolidation par les cycles de gel/dégel. Cet étude examine le processus de gel dans sol en système fermé, i.e. : sans source d'eau extérieur. Suivant ce processus, deux essais de gel ont été menés sur des échantillons de silt-sablonneux modérément gélifs initialement saturés. Le soulèvement total de la surface, les profils de températures ainsi que la pression interstitielle à la base des échantillons (partie non gelée) ont été enregistrées tout au long des tests. La teneur en eau finale a été mesurée dans la partie non gelée à la fin des tests. Il a été observé que la croissance de lentilles de glace a menée à une diminution substantielle de la pression interstitielle et ultimement au drainage de la partie de sol non gelée. De plus, l'absence de source d'eau externe n'a pas entrainé une diminution importante du taux de soulèvement au gel.

1 INTRODUCTION

Laboratory and field experiments demonstrate that substantial dewatering occurs in some soils subjected to freeze–thaw cycles. This phenomenon is often used to facilitate the reclamation process of mining tailings (Dawson et al., 1999). Although frost heave and thaw is typically considered to be a problem of volumetric soil expansion upon freezing and weakening upon thawing, the formation of ice lenses may also lead to dewatering and consolidation in the adjacent unfrozen soil. As ice lenses grow, pore pressure in the soil around ice lenses decreases and tends to draw water from unfrozen zones, triggering migration of water in soil. This in turn may result in increases in the effective stress, and therefore consolidation, or decreases in moisture content and saturation in soil away from the ice lenses. Through a series of laboratory tests, this study examines the mechanism of frost dewatering of fine-grained soils in a closed system by exploring the frost heave process in soil with no external water source. The focus will be placed on changes in pore pressure and water content in the unfrozen soil zone induced by freezing.

2 BACKGROUND

Traditionally, one of the principle mechanisms thought to be responsible for freeze thaw consolidation was the change in soil fabric induced by the growth of pore ice, different from segregated ice lenses (Chamberlain and Gow 1979). As ice initially forms in the largest soil pores, due to the volumetric expansion of water upon freezing, the larger pores exert pressure on the smaller surrounding pores and compress them. This process alters the soil fabric, since the larger pores get larger and smaller pores get smaller. When the soil thaws these larger pores will collapse slightly which ultimately leads to an overall consolidation of the material. Since no moisture migration takes place this is referred to as closed-system freeze-thaw consolidation (Stahl and Sego 1995). For this mechanism it is important to note that consolidation occurs directly in the frozen soil as a result of ice forming.

However, it is also possible for freezing to induce consolidation in the adjacent unfrozen soil due to frost action in the frozen zone. Frost heave is caused primarily by the formation and growth of segregated ice lenses. As a soil freezes a frost front, the 0 °C isotherm, will form and penetrate the soil, creating distinct frozen and unfrozen zones. However, at the interface of these two zones, where temperatures are slightly below the bulk freezing point of water, a significant amount of pore water exists in a liquid state in thermal equilibrium with the pore ice. This region is referred to as the frozen fringe. Owing to the presence of the liquid water, the frozen fringe possesses some hydraulic conductivity and negative pore pressures may develop due to interactions at the ice-liquid interfaces. Consequently, segregated ice lenses form and grow from the migration of water from the unfrozen soil to the frozen through this frozen fringe.

Under most conditions, the ground freezes from the top downward, which implies that for ice lenses to form and grow, pore water must migrate upwards as illustrated in Figure 1. One may conclude that as the ground freezes pore water must first, flow opposite to the gravitational potential gradient and second, displace the total soil mass above the active ice lens. From a thermodynamics perspective, these two conditions can both be satisfied as the system approaches a condition of greater enthalpy as the water flows upward (Ozawa 1996). This is due to the physical properties of water which cause it to contain more energy in a liquid phase than a solid phase at the same temperature (the difference in energies is referred to as the latent heat of freezing). It is possible for some of this released internal energy to produce work in the system by displacing the overburden weight. Based on this principle, it is theoretically possible for the frost heave process to displace a stress of up to 334 MPa.

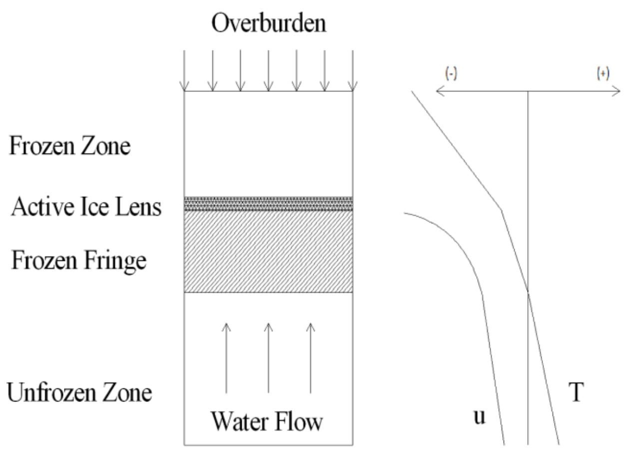

Figure 1. Schematic representation of the frost heave process.

Frost heave is essentially a ground water flow process. Hydraulic gradients develop which lead to pore water migration in the unfrozen soil. Growing ice lenses act to reduce water pressure and withdraw water from the unfrozen soil in the vicinity of the active ice lenses. As water is withdrawn, another source of water must replace it. If no source is accessible, the unfrozen soil releases pore water. Herein lies the potential mechanism for frost induced consolidation and dewatering.

A substantial body of research exists on the frost heave process dating as far back as the 1930s (Taber 1930, Beskow 1935). Several numerical models have also been developed to describe the heave rate, such as, but not limited to: the rigid ice model (O'Neil and Miller 1985), the segregation potential concept (Konrad and Morgenstern 1981), and the porosity rate function (Michalowski 1993). Many experimental investigations have been conducted regarding frost heave, including the works of: Chamberlain 1981, Konrad and Seto 1993, Fukuda et al. 1997, Hermansson and Guthrie 2005. In laboratory experimental studies, frost heave tests typically involve freezing an undisturbed or reconstituted cylindrical soil sample uniaxially in a stepped manner, the temperatures at the ends of the soil sample are either held constant, stepped, or ramped with temperatures decreasing linearly. Generally, stepped conditions are most common and are recommended for determining the soil segregation potential (Konrad 1987). Tests with ramped temperatures are more suitable for investigating the influence of the frost penetration rate on the heave rate.

Consolidation and decreases in the water content in the unfrozen zone have been observed on a small scale in frost heave tests with external water sources (Seto and Konrad 1994, Hansson et al. 2004). However to date, limited experimental investigations have been conducted to examine frost heave and moisture migration in closed systems with no external water source.

3 TESTING MATERIALS AND EXPERIMENTAL PROCEDURE

The objective of this experimental study is to examine the change in water content in the unfrozen soil zone. Two one dimensional frost heave tests with the same freezing parameters were conducted on soil samples prepared using the same method. The duration of these tests are 72 and 212 hours, respectively.

3.1 Frost-Heave Testing Apparatus

The one dimensional frost heave test apparatus used in this study is illustrated in the schematic diagram in Fig. 2. The sample is contained in a rigid plastic cylindrical "split-mould" with an inside diameter of 99.5mm and height of 300mm. Freezing conditions are imposed through two aluminum heat exchangers located at the top and bottom of the soil column. The temperatures in the heat exchangers are controlled by circulating an ethylene glycol and water mixture. The glycol-water mixture is stored in a commercial freezer at approximately -30°C and the circulation rate for each exchanger is controlled by temperature control units which allow for a specified temperature within +/- 0.05°C. O-rings and silicon grease create a seal between the top heat exchanger and the inner walls of the split-mould and allow for free axial movement similar to a piston. The bottom exchanger is fixed and sealed to the mould using silicon glue. The top plate is connected through a loading ram to a compressed air powered bellofram, allowing for uniaxial loading of the sample. Porous stones are positioned between the heat exchangers and the soil sample and are connected to external water supply lines. During the frost heave tests conducted in this study, the supply line from the top of the sample was closed and the bottom line was connected to a pore pressure transducer.

In order to minimize lateral heat flow, the outside of the mould is wrapped in 57mm thick flexible foam rubber insulation providing a total thermal resistance (*R*-value) of approximately 1.93 $m^2 \cdot K \cdot W^{-1}$. Furthermore, the test apparatus is located in a thermally controlled chamber which maintains an internal ambient air temperature varying between 3 and 6 ºC. The mould is instrumented with seven thermocouples, with a precision of +/- 0.05°C, positioned along the height of the sample and spaced 25mm apart starting at 25mm from the base. Thermocouples were selected over more precise thermistors or RTDs due to their perceived durability. The side friction between the soil sample and the mould is minimized by constructing the mould out of Polyoxymethylene, which has a coefficient of friction comparable to Teflon, and coating the inside wall with lithium grease.

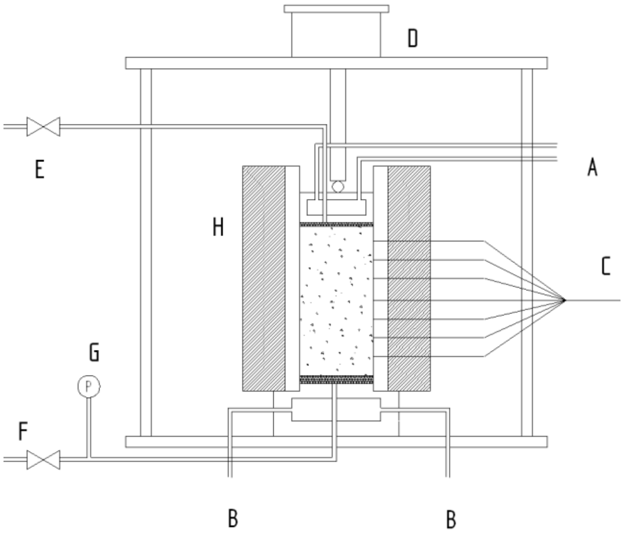

Figure 2. Frost heave test apparatus schematic; (A&B) Coolant lines to the top and bottom heat exchanges, respectively; (C) Thermocouples; (D) Compressed air powered belofram; (E&F) Water and drainage lines; (G) Pressure transducer; (H) Insulation.

3.2 Testing Material

A natural sandy silt was used in this study. The physical properties of the soil are summarized in Table 1. This particular soil was selected because it is frost susceptible with a relatively high hydraulic conductivity which allows for short consolidation time when preparing samples from a slurry.

Table 1. Physical Properties of Testing Soil

Liquid limit (%)	18.7
Plastic limit (%)	17.5
Sand (%) (0.075-2mm)	49
Silt (%) (0.005-0.075mm)	35
Clay (%) (<0.005mm)	16
Specific Gravity	2.73

In order to determine the compressibility characteristics and hydraulic conductivity of the testing material, a strain controlled oedometer test was conducted on a soil sample prepared using the method as outlined in the following section. Figures 3 and 4 present the e-*ln*p curve of the specimen and the relation between the hydraulic conductivity and void ratio, respectively. According to the test results, it is concluded that the material has low compressibility and relatively high permeability, consistent with over consolidated silty soils.

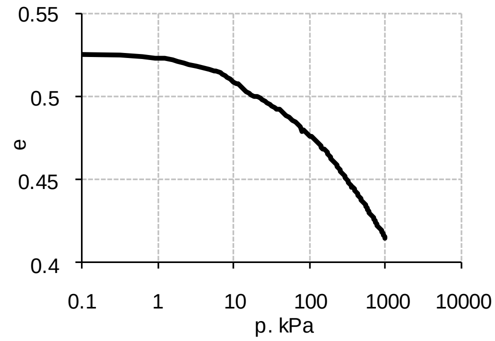

Figure 3: Consolidation characteristics of the sandy-silt.

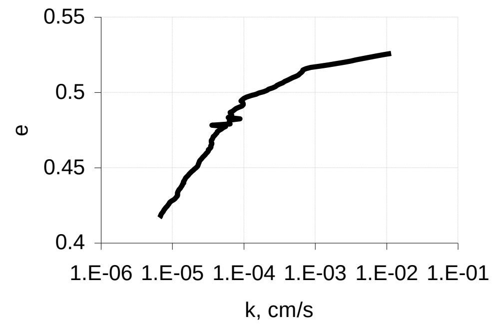

Figure 4: The variation of hydraulic conductivity with the void ratio.

3.3 Sample Preparation and Testing Procedure

Samples were prepared by first mixing dry soil and water to produce a slurry with a water content of 35%, approximately twice the liquid limit of the soil. The slurries were then placed into a vacuum chamber in order to obtain completely saturated specimens. The de-aired slurries were next poured into the mould of the frost heave test apparatus and consolidated using the loading bellofram with drainage at both ends. Samples were first consolidated to 100 kPa for approximately 24 hours, or until consolidation was complete, and then unloaded to 20 kPa and allowed to rebound for another 24 hours producing an over consolidation ratio, OCR, of 5. The high level of overconsolidation was used to maximize the frost susceptibility of the resulting specimen (Konrad 1989). Fully saturated samples prepared using this technique were approximately 200mm tall with void ratios of approximately 0.53 prior to frost heave test. Once consolidated and unloaded, valves connected to drainage lines at both ends of the sample were closed for the remainder of the experiments.

Next, the temperatures at both ends of the sample were cooled to an initial temperature of 4.0°C for 24 hours, allowing the sample to reach an initially uniform thermal steady state. The freezing test on the sample was conducted by cooling the top end of the sample to -3.8°C and the bottom end to 2.8°C, which were fixed for the duration of the test. This produced a nominal constant temperature gradient of approximately 33°C/m through the sample. It should be noted that this temperature gradient is significantly higher than what would be expected in the field but was the lowest gradient practical for the apparatus used in this study. During the frost heave test, the temperature distribution along the length of the sample, the pore pressure at the base of the sample, and the displacement of the top heat exchanger were monitored using various transducers and recorded at two minutes intervals.

The freezing tests were terminated after freezing conditions were applied for a specified duration. The mould was next removed from the frost heave testing apparatus and the frozen specimen was quickly extracted from the split-mould. Samples were collected from the unfrozen zone along the length of the specimen for water content determination. These samples were slightly less than 1cm thick and were collected 20mm apart starting at 10mm from the bottom porous stone.

A conventional stepped freezing frost heave test, with an external water source, was conducted on the same soil prepared in the same manner in addition to the two tests mentioned previously in order to determine frost susceptibility. The segregation potential of the same soil with the same applied surcharge of 20 kPa was found to be 55.8 mm^2/°C·day using the approach outlined by Konrad (1987), indicating the material is moderately frost susceptible.

4 RESULTS AND DISCUSSION

4.1 REPEATABILITY OF TESTS

Table 2 summarizes the properties and the corresponding results for two specimens prepared using the method described in the previous section. It can be concluded that the sample preparation procedure produced sufficiently consistent samples to allow for direct comparison, even though a small difference in void ratio between the two specimens was observed. Figure 4 further compares the temperature profiles along the height of specimens in the two tests. It appears that the imposed freezing conditions were consistent between both samples, which implies that the testing equipment and procedure were reliable and repeatable.

Table 2. Comparison between the two prepared samples.

Sample Characteristics	Test I	Test II
Initial Height (mm)	198.7	194.9
Initial Void Ratio	0.537	0.523
Initial Dry Density (kg/m^3)	1763	1779
Duration (hours)	72	212
Total Surface Heave (mm)	6.21	10.68
Observed Segregation Potential (mm^2/°C-day)	42.6	39.3

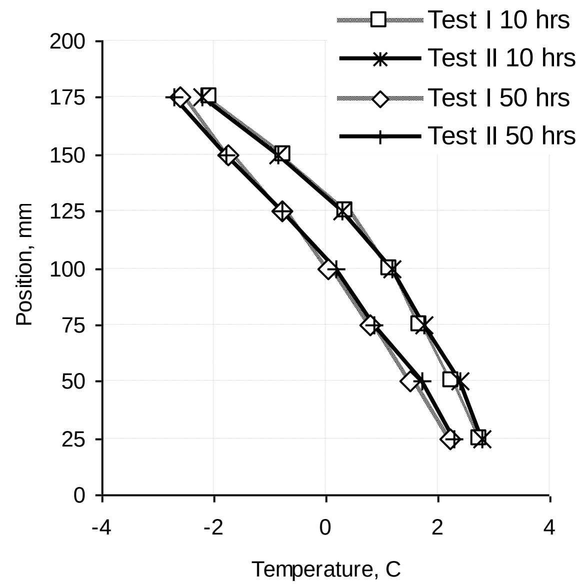

Figure 5: A comparison of recorded temperature profiles along the sample height at 10 and 50 hours.

4.2 FROST-HEAVE IN CLOSED-SYSTEMS

Figure 6 presents the measured position of the 0°C isotherm during the two tests. In both cases, the frost front quickly penetrated the soil at the beginning. With the continuation of the tests, the frost front gradually approached a steady state position, which was approximately 105mm from the base of the specimen. The data in Figure 6 shows this position of the frost front was reached at approximately 50 hours after freezing test began.

Even though the system was closed with no external water source, the variation of specimen heights with time as presented in Figure 7 clearly shows significant frost heave. Comparing the two samples it appears that they both demonstrated relatively consistent heave rates within the first 72 hours. It should be noted that heaving continued throughout the whole test for both specimens, even after the position of frost front reached steady state at approximately 50 hours, which may imply that moisture migration continued to take place while the freezing fringe stopped moving downward.

With regards to the pore pressure at the base of the unfrozen soil, Figure 8 indicates that prior to heaving the pressure increases to approximately 20 kPa. This is consistent with observations reported in the literature that pore water is sometimes expelled prior to heave initiating in frost heave experiments (Nixon 1991). However, as soon as heave begins, the pore pressure drops dramatically to approximately -50 kPa. The drop of pore pressure at the base of the specimen can be considered an indicator for upward moisture migration. When comparing Figures 7 and 8, one observes that the dramatic drop in pore pressure occurred simultaneously with the initial heave at the top of the specimen. After this the pore pressure increases and, from there on, varies in an irregular and somewhat oscillatory manner. After the first local minimum of pore pressure is reached we see less agreement between the two tests. It is interesting to note that in spite of this difference in basal pore pressure the heave rate of the two samples remains remarkably consistent. More investigations are necessary to understand the mechanism resulting in the oscillatory variation in pore pressure at the bottom of the specimen.

The sharp drop in pore pressure indicates that the formation of ice lenses begins to draw pore water upward from the unfrozen zone. The increase in effective soil stress caused by the decrease in pore pressure may have lead to some consolidation in the unfrozen soil. Consolidation alone could theoretically release the pore water required by segregated ice growth in a manner similar to a confined aquifer. However, it is unlikely that this mechanism alone could release sufficient water with the unfrozen soil remaining saturated. To illustrate this, let us assume that the sample were to remain completely saturated, with no external water source, the only way for the soil to heave is through the volumetric expansion of water upon freezing, which amounts to approximately 9%. Considering the second sample tested, with an initial height and porosity of approximately 195mm and 0.35 respectively, the maximum heave possible would be approximately 6.1mm (9% multiplied by 0.35 and 195). However 10.7mm of heave was observed, implying unsaturated conditions must have developed.

Moreover, due to the high initial overconsolidation ratio, the soil specimens have relatively low compressibility, as illustrated in figure 3. Therefore with the total observed changes in effective stress of approximately 100 kPa not significant amount of pore water could be released. As such, it is more likely that the suction generated is large enough to cause the pore water to vaporize leading to unsaturated conditions. This may also explain the severe variation in the pore pressure observed after its first local minimum is reached. These results demonstrate that the driving forces of ice lens growth are not completely inhibited by a lack of external water supply and that they are significant enough to un-saturate, or dewater, soils. It should be noted that the measured pore pressure at the bottom of the specimen, which is not high enough to cause cavitation of pore water, does not reflect the variation of pore pressure near the frozen fringe. Further investigation is necessary to understand the mechanism of de-saturation in the unfrozen soil.

Figure 9 indicates that the water content in the unfrozen soil decreases with time. For the sample frozen for 212 hours the water decreased from an initial value of approximately 20% to between 17 and 18%. In the sample frozen for 72 hours, the decrease in moisture content occurs mostly near the frost front while the soil at the base remains close to the original moisture content, implying the soil at the base is still close to saturation. On the other hand, the sample frozen for 212 hours displays a more uniform moisture content profile. Visual observations indicate that the unfrozen soil, particularly in the 212 hour sample, was unsaturated and began to crumble upon removal from the split mould. For the 212 hour sample, the thickness of the ice lens corresponding to the final position of the frost front was approximately 5mm; whereas in the 72 hour frozen sample, the final ice lens was observed to be less than 1mm thick. This indicates that in 72 hour test most of the heave was distributed over multiple ice lenses near the top of the sample.

4.3 Hydraulic Boundary Conditions and Heave Rate

The segregation potential, SP, obtained from a frost heave test with a water source, as mentioned in section 3.3 was found to be 55.8 mm^2/°C·day. For a closed system without an external water source the values of segregation potential were found to be 42.6 and 39.9 mm^2/°C·day, for the 72 and 212 hour tests respectively. It should be noted, that the procedure for determining SP defines it as the water migration velocity over the thermal gradient when the frost front reaches a constant position. The reduced values of SP indicate that the lack of water source decreased the overall frost susceptibility of the system. However, it is difficult to isolate the potential effect of consolidation on the observed frost heave. Any consolidation of the unfrozen soil will directly counteract heave due to ice lens formation. Although it is likely that some consolidation will occur in frost heave tests with an external water source, the substantial decrease of water pressure in tests on closed systems with no external water source implied that significant consolidation may have occurred in the unfrozen zone. One also expects that the frost heave in a closed system would be limited owing to the finite amount of water available for ice lens growth. In this case, with no external water supply, the heave rate at 50 hours may be quite larger than at 500 hours or 4 months. Therefore it is difficult to come to any definitive conclusions regarding the frost susceptibility of a soil system with a water supply and without.

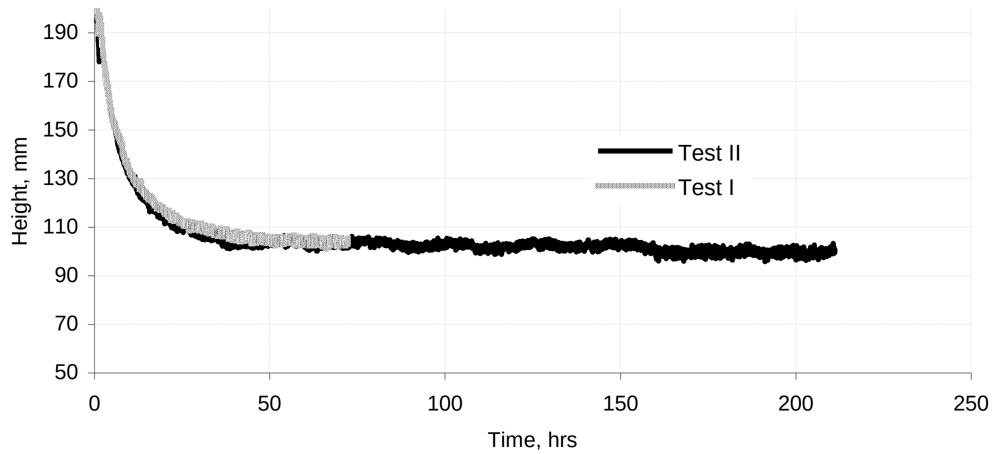

Figure 6. The position of the 0°C isotherm throughout the tests as measured from the sample base.

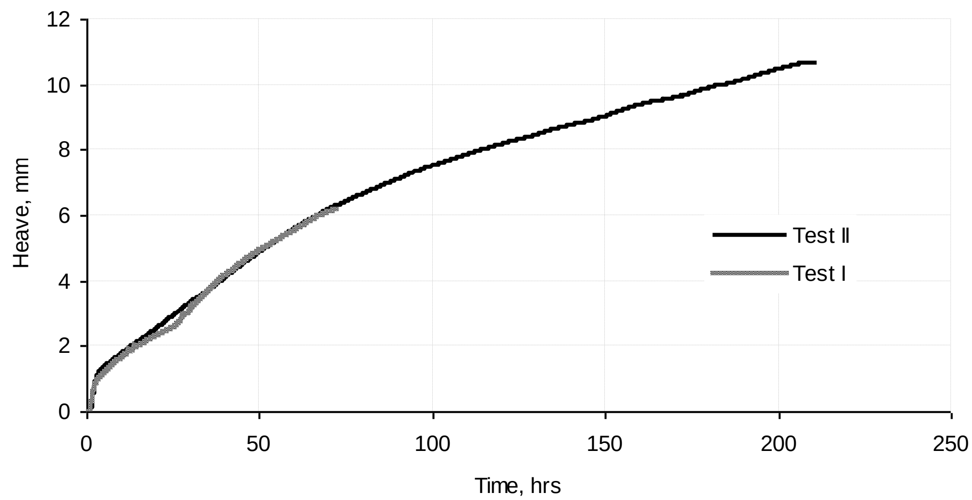

Figure 7. Total observed surface heave.

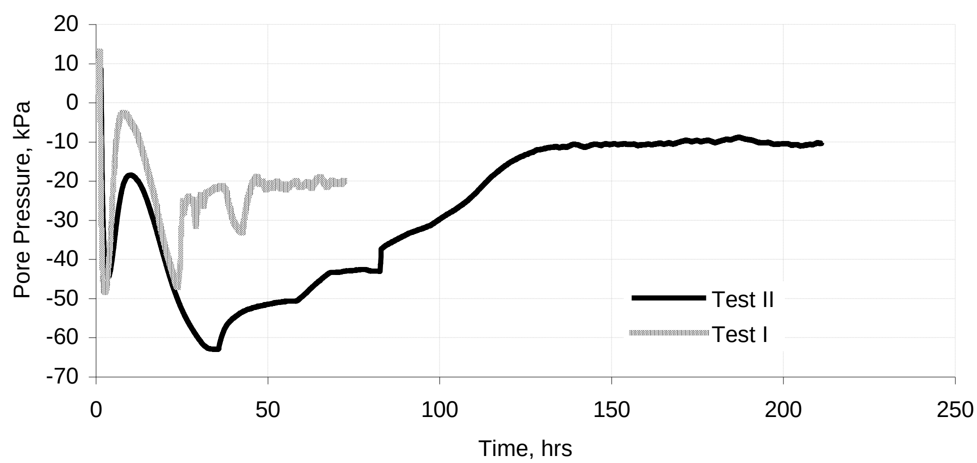

Figure 8. Pore pressure recorded at the base of the soil sample.

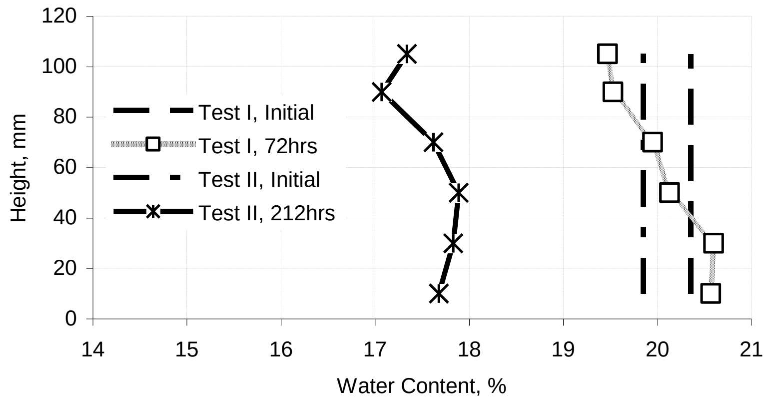

Figure 9. Profile of the final water content in the unfrozen soil.

5 CONCLUDING REMARKS

The present study of frost heave in a system with no external water source has led to the following conclusions:

(1) Under unidirectional stepped freezing conditions, frost heave may occur in a soil system without an external water source by the removal of water from adjacent unfrozen soil. However, when compared to freezing with a water source the overall frost susceptibility, as defined by the segregation potential, was observed to decrease by approximately 30%.

(2) With no external water source, the suction generated due to segregated ice growth is sufficiently high to un-saturate, or dewater, the initially saturated adjacent soil.

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