Suction measurement in freezing soils using pore pressure transducers

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Abstract. Frost heave is major problem for infrastructures build in cold regions. Frost heave occurs due to suction (negative pore water pressure) generated due to the freezing process close to the frost line, i.e., at the frozen fringe. To understand and predict these negative pore water pressures is a key factor to accurately calculate the segregation heave, i.e. heave related to the formation of ice lenses. Segregation heave is the major part of the total heave and also the most challenging to predict. Many attempts have been presented in literature where the generated suction during freezing is related to temperatures, temperature gradients, grain size of the freezing soil etc. Very few laboratory tests have been presented in which the actual suction is measured during the ice lens formation process and compared with theoretical estimations. One reason is that these measurements are challenging. This paper presents results from laboratory measurements of generated suction during freezing. Laboratory tests were conducted on a silty soil sample and suction was measured at the frozen fringe using small pore pressure transducers (PPT’s). The samples were subjected to one-dimensional freezing from top to bottom in an open water system at a constant temperature gradient. Temperatures were measured at various points along the height of the soil sample while suction was measured at middle of the sample. Test results have shown that PPTs do not show pressure change in long-term static pressure test under sub-freezing temperature. For suction measurement at the frozen fringe, pore pressure readings should be measured at various points along the sample height.

1. Introduction and background

One challenging problem for the infrastructure in cold regions is the consequences due to frost action in soils. Frost heave occurs due to phase transformation of water to ice due to sub-freezing temperature. Thaw weakening or thaw settlement occurs due to melting of ice in summer period. Frost heave not only occurs because of 9% volumetric expansion of water during phase transformation, but also due to the formation of ice lenses in the frozen zone giving segregation and volume expansion. These ice lenses are formed due to suction or negative pore pressure generated at the frozen fringe [1–3]. Suction generated in the frozen fringe creates the hydraulic gradient across the frozen fringe, i.e. from the frost line to the warm side of the warmest ice lens. Hydraulic gradient causes transport of water from unfrozen zone to the growing ice lens across the frozen fringe. This extra water feeds the ice lenses and makes them grow. The segregational heave is the major part of the total heave, and this is also verified by the observations in field [1,2].

Segregation potential theory states “at the formation of final ice lens, the water intake flux is proportional to the temperature gradient across the frozen fringe” [4]. This proportionality index is called segregation potential (SP). SP theory is convenient to use because SP can be easily determined using...
laboratory testing. SP value is dependent on the suction generated at the frozen fringe among other several parameters (temperature gradient, stress at frost front, type of soil and rate of cooling of frozen fringe etc.). Therefore, it is important to accurately measure the suction using laboratory testing [4–8].

Few attempts have been made to predict suction using laboratory testing [2,3,15,16,7–14]. Manometers have been used to predict pore pressure at the bottom of the soil sample whereas the frozen fringe lies in direct contact with the frost line and therefore at different locations as frost front propagates. This leads to the less accurate measurement of pore pressure at frozen fringe [2,3,10,14]. The reason behind limited laboratory tests is the complex measurements. For the measurement of suction at frozen fringe, current laboratory setup present at Lulea University of Technology is used with addition of miniature pore pressure transducers (PPT’s) [17].

This paper presents a laboratory test performed to measure the suction at frozen fringe using pore pressure transducers. The paper has three sections: the first section (Material and methods) describes the properties of soil sample used and the laboratory setup at testing; the second section (Results and discussions) shows the result obtained from the laboratory results; and the third section (Conclusions) displays the lesson learnt from the laboratory tests along with the future work.

2. Material and methods

2.1. Sample preparation
A disturbed sample of sandy silt of specific gravity 2.70 was used. The particle size distribution curve in figure 1 shows the type of soil, which is silt. This soil was chosen as it is a relatively frost susceptible material. The soil sample was prepared by means of hand compaction in a cylindrical cell of diameter 10 cm and was compacted in five equal layers to a height of 10 cm with initial water content of 10%. Initial water content of 10% is used for good workability during hand compaction. Dry density of 1600 kg/m³ and porosity value of 0.4 was achieved after hand compaction. The sample is saturated for 24 hours by allowing water movement from bottom to top under low hydraulic gradients to prevent particle sorting within the sample.

2.2. Pore pressure transducers
Pore pressure transducer (PPT) from Keller AG, of diameter 7 mm was used to measure suction. PPT is shown in figure 2. The pressure range of this transducer is between 0 to 500 kPa and is compensated for temperature range of 10-40 °C. Filter stone is used to protect transducers from soil material. When pore pressure changes in soil, this pressure change enters the transducer body and, then recorded in computer.

2.3. Laboratory setup
The laboratory setup for freezing and thawing tests is shown in figure 3 [17]. This setup is modified by using PPT at mid-depth of soil sample which can be observed in figure 3. A soil sample is placed in the transparent cell. 7 thermocouples are placed along the sample height. Two thermocouples are placed at top and bottom of the sample. Rest five thermocouples are at equidistant of 2 cm to each other as shown
in figure 3. They are used to measure the temperature at different positions. Top cap and bottom cap is connected to two cooling units which provides cool and warm end temperatures to the sample. Linear variable differential transformer (LVDT) is placed at top cap to measure the frost heave. A 7cm thick layer of insulation is used around the test cell for one dimensional heat flow from bottom to top. Water access is provided from bottom and water level is kept equal to the bottom of the sample during start of freezing test. PPT1 is connected by using three valve connector at the middle of soil sample. A second transducer, PPT2 is kept outside of insulation as a reference reading and also to track the changes in atmospheric pressure. For detail description of the laboratory setup, see [17]. The duration of the test was 13 days and only freezing test was performed.

![Figure 3. Frost heave laboratory test setup for pore pressure measurement.](image)

2.4. Test procedure
Two different tests were conducted. One test was to study the performance of PPT’s in relation to the temperature, whereas other was for the suction measurement during freezing test. The behaviour of two PPT’s with respect to temperature were studied at -6 °C for initial pressure head of 9.4 kPa. They were calibrated for temperature range of 10 to 40 °C. The pressure head was provided by using standpipe filled with mixture of 50% pure ethanol and 50% water to prevent ice formation at temperatures below 0 °C. Sub-freezing temperature was provided by immersing PPTs in temperature bath filled with mixture of 50% pure ethanol and 50% water.

For second test, the experiment was started with the temperature of 2 °C along the entire specimen after saturation the soil sample has ended. After the steady state phase, the top cap temperature was changed to -4 °C step wise, while keeping the bottom cap and surrounding temperature at +2 °C. The water level was kept constant at sample bottom. Water access is provided during entire test. The readings for all measurements were recorded at an interval of 10 minutes. Two PPTs were used for suction measurement. PPT1 corresponds to the suction measured inside the soil sample whereas PPT2 was the reference pore pressure measured outside the insulation layer.

3. Results and discussions

3.1. PPT behaviour at -6°C
The pore pressures for the two PPTs during long-term test (four days) at -6 °C are shown in figure 4 and the corresponding temperature readings are shown in figure 5. Figure 4 shows that pore pressure transducers behave different to each other at same temperature below zero. Between two PPTs there are
approximately a difference of 3.8 kPa when temperature was changed from -1°C to -6 °C. This difference is not acceptable because both PPTs had same pressure head in the start of test and therefore there should not be any difference between the two after temperature change, as the pressure head was kept constant. There are two reasons for this difference. One is due to the improper saturation of the transducers and other is different thermal coefficient of the PPTs.

From figure 4, it can also be observed that both transducers follows the same trend. The pressure change in PPTs is due to the change in the atmospheric pressure as both PPTs follow the similar trend. The difference between two PPTs shows that there is no long term effect on pressure change in PPTs after four days in temperature bath at -6 °C. Therefore, pore pressure transducer can be used in sub-freezing temperature by compensating the thermal coefficient difference between different transducers. Also, for minimising the pressure difference, proper saturation of PPTs is must, as during the test, air bubble in front of PPTs was observed.

![Figure 4](image4.png)  
**Figure 4.** Pressure change in two pore pressure transducers, PPT1 and PPT2 at approx. -6 °C for four days.

![Figure 5](image5.png)  
**Figure 5.** Temperature curve of temperature bath for corresponding pressure change of PPT at -6 °C.

### 3.2. Suction measurement during freezing of soil

The thermocouple reading for entire test is shown in figure 6. Thermocouples T1 at top to T7 at bottom represents the temperature from top to bottom of the sample. The thermocouple reading at T1 and T7 are in agreement to the applied temperatures at top and bottom of the soil sample. Thermocouple T5 was damaged during the test as it shows the temperature reading between 20 °C and 30 °C (see figure 6) while the maximum temperature applied at the bottom of the sample was +2 °C. Temperature increases across the length of the sample in relation to heat transfer from bottom to top cap, see in figure 7. Figure 8 shows the frost heave recorded by LVDT during freezing of the sample. This graph shows that there is an increase in the heave of the sample after 48 hours of test.

Suction measurement during freezing test is shown in figure 9. PPT1 corresponds to the suction measured inside the soil sample whereas PPT2 was the reference pore pressure measured outside the insulation layer. The difference between PPT1 and PPT2 shows the suction during freezing of the soil sample. The difference between transducers is negative, which shows that the suction increases during freezing of the soil sample. But, this measurement raises the question about the accuracy because PPT was installed at mid-depth of soil sample, which might be at the location of the frozen fringe or not. Using temperature readings from figure 7, the depth of frozen fringe is 7.2 cm (calculated by interpolation). Also, this measurement depends on the saturation of the pore pressure transducers. The pore pressure transducers behaves differently with respect to sub-freezing temperature, which affects the results. In this measurement, PPT was installed at the face of soil sample. Hence, it might have some effects from thermal behaviour of the PPT material. Therefore, suction measurement requires more number of transducer readings along the sample height to measure suction at frozen fringe.
Figure 6. Thermocouple readings for suction measurement test during freezing. T1 to T7 represents the temperature from top to bottom of the sample. T5 was damaged during the test.

Figure 7. Temperature variation across sample height after 10 days. Thermocouple T5 reading is not considered in this plot.

Figure 8. Frost heave during freezing of sample.

Figure 9. Pore pressure during freezing of soil sample. PPT1 was used for suction measurement while PPT2 was kept out of insulation to track atmospheric pressure. Difference between both transducers shows the suction during freezing test.

4. Conclusions and future work
Based on the above tests, following conclusions are drawn:

- Pore pressure transducer has no long term effect on static pressure when they are subjected to sub-freezing temperature.
- For suction measurement during freezing of soil, PPTs should be calibrated for thermal coefficient effect and should be fully saturated with low viscous fluid which will not freeze under sub-freezing temperature.
- For minimizing the effect of thermal coefficient in PPTs, they should be kept outside of the insulation layer.
- Pore pressure should be measured at various points along the sample height for suction measurement at frozen fringe.
- For future work, more test will be conducted for longer period based on above drawn conclusions.

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