Mechanism of thawing
Amin Zeinali1*, Tommy Edeskär1 and Jan Laue1

Abstract: Freezing–thawing phenomena have been studied at laboratory scale for decades with various techniques and test setups. In this study, a freezing–thawing laboratory apparatus was supplemented with a camera in order to get a better understanding of ice formation during the freezing period and ice melting during the thawing period. The results from three thawing tests with identical samples but different boundary conditions are presented here. Water intends to migrate upward even when the entire frozen part has been thawed. That would cause excess pore water pressure and softening of the soil after the thawing period as well. Upward water migration after the thawing period is due to changes in thawed soil properties such as permeability and fine particle redistribution. The rate at which thawing takes place is a very important factor for thawing conditions. Moreover, freezing condition, i.e. access to water, has a high impact on thawing soil. If the volume of ice lenses is sufficient, frozen soil would fluidize during thawing.

Subjects: Soil Mechanics; Foundations and Piling; Pavement Engineering

Keywords: freezing; thawing; image analysis; frost actions; laboratory freezing-thawing tests; thaw settlement

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PUBLIC INTEREST STATEMENT
Frozen ground engineering is an important factor in design in cold region areas. When the soil is exposed to freezing temperatures, the soil moisture changes from water to ice, resulting in water volume expansion of 9%. In addition, transfer of external water (due to the suction) from deeper layers to the freezing area occurs constantly. Consequently, the soil heaves (frost heave), depending on the amount of available external water, freezing period condition, and type of the soil. During thawing, due to the released water from accumulated ice lenses, the volume of water in the soil increases. Pore water pressure increases in the soil body, which decreases the stability of the soil. Bearing capacity loss in the pavement may cause load restriction during the spring thaw period. In this paper, we focus on the thawing process in laboratory scale. We have captured the thawing process (phase changes from ice to water) by camera as well.
1. Introduction

The frost action and the phase change of water (from liquid to solid) in a soil body, due to freezing and thawing of soils, change the properties of the soil. It has been recognized that freeze–thaw cycling has a considerable impact on the structure and thus the geotechnical properties of soils (Alkire & Morrison, 1982; Chamberlain & Gow, 1979; Qi, Vermeer, & Cheng, 2006; Cui, He & Yang, 2014). In the field of engineering, most research and design has focused on the effects of freezing of soils, e.g., frost heave (Guymon, Berg, & Hromadka, 1993; Zhou, Wei, Wei, & Tan, 2014), effect on strength properties (Brandl, 2008; Miller, 1980), and soil classification of frost susceptibility (Chamberlain, 1981). The consequences of thawing are well known, e.g., loss of bearing capacity (Graham & Au, 1985; Launonen & Turunen, 1995; Simonsen, Janso, & Isacsson, 2002) and settlement due to consolidation (e.g., Morgenstern & Smith, 1973; Eigenbrod, Sheng, & Knutsson, 1996; Zou & Boley, 2009; among others). But the processes in the soil body during thawing are still not well observed. When we are talking about frost action in the soil, majority of the studies are about Freezing part (frost heave mechanism) and very few studied (relatively) about Thawing part. Eigenbrod et al. (1996) used X-ray to take pictures during the freezing test and compared the measured pore water pressure by the localization and extension of the frozen zone. In this study, the thawing mechanism has been studied in laboratory conditions by image analysis on soil samples subjected to mainly one-dimensional freeze and subsequent thaw cycle from the top under various conditions.

Most studies on the strength properties of thawing soils have been conducted under undrained conditions. Graham and Au (1985) have reported a significant loss in undrained shear strength soon after freeze–thaw cycles on clays. Studies on loose silt show the opposite behavior (Alkire & Morrison, 1982) probably due to the compaction effects of the freeze–thaw cycles. Simonsen et al. (2002) have documented a significant reduction in the resilient modulus soon after freeze–thaw cycles.

Freeze and thaw cycles affect the hydraulic conductivity. Clays increase the hydraulic conductivity accompanied by a thaw consolidation, e.g., Chamberlain and Gow (1979). Thaw consolidation has been studied by several researchers (e.g., Nixon & Morgenstern, 1971; Chamberlain & Gow, 1979; Eigenbrod et al., 1996; Zou & Boley, 2009). Chamberlain, Iskandar, and Hunsicker (1990) among others have inferred that the increase in hydraulic conductivity is due to both micro-fissuring and the large pores that are left after the thaw of ice crystals. Chamberlain and Gow (1979) also mention that fine particles might move out of large pores during the freeze–thaw cycle. For other fine-grained soils, the effect on hydraulic conductivity seems to depend on the initial compaction state. Dense fine-grained soil increases the hydraulic conductivity after freeze–thaw cycles (e.g., Viklander, 1998), but initially loose fine-grained soil the hydraulic conductivity decreases. Viklander (1998) suggests that there is a residual void ratio for soils subjected to freeze–thaw cycles independent of the initial compaction state. Viklander (1998) suggests that there is a residual void ratio for soils subjected to frost–thaw cycles independent of the initial compaction state.

During thawing, the soil may suffer from loss in strength, i.e., thaw weakening. The key factors influencing the loss in strength are the thaw rate, amount of frozen water in the voids and in segregated ice, the drainage ability of the soil, and the load the soil is carrying (Launonen & Turunen, 1995; Doré, 2004; Shoop, Affleck, Haehnel, & Janoo, 2008; among others). During thawing, the soil profile is partly frozen and the frozen part remains in layers. The frozen soil can be considered to be impervious due to the very low hydraulic conductivity in frozen soil (Watanabe & Flury, 2008). Therefore, the released water from thawing is prohibited to drain downward due to the existing frozen soil and becomes trapped between the frozen zone and the surface.

The scope of this study has been to visualize the thawing process by image acquisition and interpretation of the images. In this study, ice formation and ice melting during freezing–thawing tests were monitored. Prior to thawing, the soil sample has been subjected to freezing from the top. The freezing cycle was ended after thermal equilibrium was reached and the thawing cycle was
documented by image analysis until the whole sample had thawed and reached a new thermal equilibrium.

2. Methods and material

2.1. Sample
A frost-susceptible sandy silt from Björsbyn, see Figure 1, was selected for this study. The basic soil properties of the selected soil are presented in Table 1. The maximum dry density was determined by the standard Proctor test.

The test soil was dried before sample preparation. To increase the workability for compaction of the soil, 10 mass-% of water was added to the dried soil. The sample was compacted into the test cylinder by hand using a small proctor type hammer with low energy in five equal 2-cm thick layers in a transparent plexiglass cylinder of 5 cm in diameter and height of 10 cm. The sample properties after preparation are given in Table 2.

Thermocouples were pushed into the soil sample through predrilled holes in the wall of the cylinder along the length axis. The test was conducted on two identical samples put in two freezing cells that were operated simultaneously. The freezing cells are described in detail in Zeinali, Dagli, and Edeskär (2016) and is schematically shown in Figure 2. After sealing the holes in the cylinder, the sample was placed on the bottom cap in the test apparatus, on a porous stone and covered by a filter paper. The bottom cap controls the access of water and controls the thermal conditions at the bottom. The hydraulic gradient at the bottom of the setup was controlled by leveling of an external water source.

![Grading of Björsbyn material.](image)

**Figure 1. Grading of Björsbyn material.**

**Table 1. Basic properties of the Björsbyn material**

| Specific gravity (Gs) | Maximum dry density (ρdMax) | Uniformity coefficient (Cu) | Coefficient of curvature (Cc) |
|----------------------|----------------------------|-----------------------------|-----------------------------|
| 2.67                 | 2000 kg/m³                 | 2.63                        | 0.8                         |

**Table 2. Sample properties after molding in the cylinder**

| Height (cm) | Dry density (ρd) | ρd/ρdMax | Water content (w) | Porosity (n) |
|-------------|------------------|----------|-------------------|--------------|
| 10.2        | 1600 kg/m³       | 0.8      | 0.1               | 0.4          |
The top cap was used to freeze and thaw the sample. The temperature at the top and bottom caps was controlled by two cooling units (LAUDA ECO model 1050 S). The whole apparatus was limited to a maximum of 6-cm frost heave. The soil sample and the surrounding cylinder were free to lift with the soil sample during freezing in order to minimize the friction between soil and apparatus. The heave and thaw movements were measured on the top cap by a linear variable differential transformer (LVDT). The two frost heave cells were contained in a cold chamber where the ambient temperature was set to 4°C. The temperature was measured by temperature gauges in the cold chamber, at the top and bottom cap of the equipment and at levels 0, 2, 4, 6, 8, and 10 cm at the initial height of the soil sample before the start of the experiment.

After putting the cells in the apparatus, the top cap was placed carefully including the clamp which allows the top cap to move together with the cell during the freezing test. Prior to adding insulation, all thermocouples and LVDT were connected to data loggers. The sampling time was set to 5-min and 1-min intervals during the freezing test and during the thawing test, respectively. In order to create a steady start state of the test, when cells were placed in the cold chamber, both cooling units (top cap and bottom cap) were set to +4 °C. The surrounding temperature was also set to +4 °C by means of a control unit of the cold chamber. An insulation layer of rockwool around the cylinder was used to ensure one-dimensional conditions. An opening in the insulation layer was created to get access for the camera to track the heave and thaw process, see Figure 3. As a result, due to the opening, there was not a fully one-dimensional heat flow. A 7 × 15 cm² window of the thermal insulation on one side of the cylinder was opened and a camera (Canon EOS 550D equipped with Canon zoom lens EF-S 18–55 mm) was placed approximately at 20 cm to the sample, outside the freezer, in order to monitor visually the freezing–thawing cycle. In order to provide enough light, three LED light sources were placed around the insulation opening which were assumed negligible in heat generating. Figure 3 shows the camera and opening of one of the samples. That means data from data logger are stored at the same time the camera take a picture. Therefor we have all data for the corresponding image.

However, a fully insulated sample (one-dimensional heat flow) was running simultaneously. The freezing test was started when the entire sample was at the constant temperature +4 °C.
During the freezing cycle, the top cap temperature was held constant at −4°C. The access to water was controlled by opening or keeping the valves to the water supply depending on the test sequence. When thermal equilibrium was reached in the freezing cycle, the thaw cycle was initiated by setting the top cap temperature to 4°C. In addition, a dead load of 18 kPa was added to test 1 and test 3 on top of the samples. The thaw cycle ended when the whole sample had reached positive temperatures and thermal equilibrium was reached. The bottom cap and the surrounding temperature were maintained constant during both freezing and thawing tests.

3. Results

Three different thawing tests have been conducted in this study. Table 3 summarizes the boundary conditions and initial freezing conditions at the beginning of the thawing tests. Test 1 had unlimited access to water during the freezing cycle and subjected by an overburden load of 18 kPa during the whole test. Test 2 had unlimited access to water during the freezing cycle but had no overburden load. Sample in test 2 was subjected to different freezing and thawing gradients as well. Test 3 was conducted by a two-step freezing cycle. The first freezing step was conducted with no access to an external water source. When thermal equilibrium was reached, the second step started by providing access to water from below. The second step of the freezing cycle was ended when a new thermal equilibrium was established. The sample was subjected to an overburden of 18 kPa during the freezing and thawing cycles.

The tests have been evaluated by the readings of the thermocouples, LVDT readings, and image recordings during the thawing cycle. The frozen zone in the results is defined by the boundaries of the 0°C isotherm based on the thermal couple readings along the cylinder. Linear interpolation of the depth in between the thermocouples has been used to define the 0°C isotherm position. The deformation is here defined as the portion of thaw settlements relative to the heave of the sample during the freezing cycle. All figures of temperature and LVDT readings are set to start at least 1 h prior to the start of the thawing cycle, although the readings from the very beginning of the test are eliminated in some figures.
| Test | Sample  | Freezing conditions | Thermal gradient (freezing) | Initial sample height (cm) | Sample height after heave (cm) | Thaw time (h) | Maximum frost depth (cm) | Overburden load during thawing (kPa) |
|------|---------|---------------------|-----------------------------|-----------------------------|-------------------------------|----------------|--------------------------|-----------------------------------|
| 1    | Image analysis | Access to water | 90°C/m | 10.2 | 12.2 | 28 | 7 | 18 |
|      | Reference | Access to water | 90°C/m | 10.3 | 14.7 | 28 | 8.5 | 18 |
| 2    | Image analysis | Access to water | 80°C/m-90°C/m | 10.1 | 13.2 | 40 | 8.5 |    |
|      | Reference | Access to water | 80°C/m-90°C/m | 10.2 | 14.8 | 40 | 8.5 |    |
| 3    | Image analysis | Access to water after 24 h | 90°C/m | 10.3 | 11.7 | 60 | 7.0 | 18 |
|      | Reference | Access to water after 24 h | 90°C/m | 10.2 | 14.3 | 60 | 7.5 | 18 |
3.1. Test 1

The freezing cycle was conducted for 5 days to ensure that the sample was in thermal equilibrium at the thermal gradient 90°C/m. The resulting frost heave was more than 2 cm and the frost depth was 7 cm relative to the original surface level of the sample. The thawing cycle was initiated by sudden raising of the temperature from −5°C in the top cooling unit (providing temperature at the sample top) to +4°C. A static load of 18 kPa was applied on top of the sample for the thawing test. In Figure 4, the temperature progress during the thawing cycle is presented for the image analysis sample and in Figure 5 the fully insulated reference sample.

In Figure 6 and Figure 7, the deformation and thaw progression by time are presented for the image analysis and fully insulated samples. As seen in Figure 6, the thawing of the sample was fast, and the drop in settlement at around 3 h elapsed time took a very short time and cannot be correlated to the temperature readings. The remaining frozen zone thawing is equivalent to the ice lenses shown in Figure 8.

The image acquisition started when the thawing cycle began. Several images have been selected to describe the thawing process. The first part of the thawing cycle is presented in Figure 8. The image at time step 0 h shows the initial condition at the beginning of the thawing cycle. The location of segregated ice is visible in the left-hand side image in Figure 8. After 4 h of the thawing process, small changes in a frozen part are noticeable. The thaw depth is penetrating from the top and the heat flow mainly from the top starts to melt the ice lenses (Figure 8) at time steps 4 h to 5 h and 10 min.
At the lower thick ice lens, the melting water forms a slurry containing fine particles from the surrounding soil, see Figure 8. When the lowest ice lens melts, the trapped particles between the ice lens and the test cell surface get suspended in the melted water. After 5 h of thawing, a track of mud between the thawing soil and unfrozen soil was formed. As the non-segregated ice in the soil sample thaws, the degree of saturation increases in the thawed zone. During this process, redistribution of the grains can be observed, see Figure 8 at time 5 h. The released water from thick ice lens intents to move upward. As the ice continuously melts, the additional water migrates to the trapped persistent water, see Figure 9 at time 6 h.
At time 6 h, no water flow within the soil body can be determined by the images. The progressive images in Figures 9 and 10 show the finer particles in the void sediments and as the free water gets clearer. It is likely that fine particles migrate through the created path. It is also observed that the soil over the water crumbles into the clear water. It takes a couple of hours for the trapped water to redistribute in the thawing soil. The amount of releasing water from the thick ice lens increases dramatically toward the end of the test. Even when the entire frozen soil has thawed, thawed soil crumbles into trapped water and settled. Therefore, trapped water migrates upward after thawing as well. By the end of the test, the excess water has moved to the surface. It is observed after 20 h and lighter gray soil is the mudflow, see Figure 10. The selected images from the last few hours show the upward mudflow (in lighter gray color) and clear water is observed after 28 h, see Figure 11.

Figure 9. Selected images from the thawing cycle of the experiment covering elapsed time 6 h to 9 h.

Figure 10. Selected images from the thawing cycle of the experiment covering elapsed time 10 h to 21 h 20 min.

Figure 11. Selected images from the thawing cycle of the experiment covering elapsed time 21 h 40 min to 28 h.
3.2. Test 2
Test 2 was conducted in two steps during the freezing test. After a steady state at +4 °C, the temperature was decreased to −4°C at cooling unit in order to maintain a constant temperature gradient through the sample. Due to the problem in the controller system of the cold chamber, the surrounding temperature dropped to −1°C, see the first image from left-hand side in Figure 12. The surrounding temperature has been increasing to +8°C in 1 day, see the fourth image from the left-hand side in Figure 12. As a result, two ice lenses were formed, see the second image from the left-hand side in Figure 12 which tends to thaw after 8 h of increment from −1°C, see the third image from left-hand side in Figure 12. The surrounding temperature got unstable after 12 h again and increased to +16°C. Additional frozen layer and thawing in the frozen soil was due to the heat flow through the opening of the insulation for the image analysis sample. Therefore, the frost front penetrated deeper in this sample compared to the reference sample. A convex ice lens was formed because of the heat extraction through the opening when the surrounding temperature dropped to −1°C, see the second image from the left-hand side in Figure 12.

The frost heave was 3.2 cm for the image analysis sample and 4.6 cm for the reference sample. The following documentation includes the thawing phase after a constant temperature gradient was reached again. In Figure 14, temperature fluctuations in cold chamber and its effect on top and bottom cap is plotted during the test. Figure 14, the temperature progress during the thawing cycle is presented for the image analysis sample and in Figure 15 the fully insulated reference sample.

The frost depth at the beginning of the thaw cycle for both image analysis sample and reference sample is similar despite the difference in frost heave during the freezing cycle. The thawing period is shorter for the reference sample, probably due to the additional heat extraction through the opening of the insulation in the image analysis sample. The development of deformation was low during the thawing phase. If a longer time perspective is considered, see Figure 17, the majority of the thaw settlements occur rapidly after 25 h of thawing.

Although the top cap temperature was maintained constant, thawing has started due to the heat flow into the sample through the opening as soon as the surrounding temperature increased. Hence, thaw front is penetrating from underneath layers. Since the top cap still provides freezing temperature, the sample reaches thermal equilibrium again and the thawing process stopped. Thawing from the bottom of frozen soil is shown in Figure 12. After 30 h, the whole system including cooling units was shut down in order to conduct thawing process at a very fast rate (the whole system is exposed to room temperature), see Figure 13. No overburden load has been applied during the thawing test, and since the weight of the top cap is neglected, this test was considered with no overburden load. As it is shown in Figure 13, released water is trapped where the ice lens used to be and the water moved upward as it was observed in test 1. Since the freezing
test is conducted in two steps and for a longer period of time, the amount of excess water was more than in test 1 as was the depth of frost penetration. The main portion of the thawing occurred after shutting down the entire system which causes around 20°C in the sample, and it took 12 h out of 45 h thawing period.
3.3. Test 3

Test 3 was conducted without access to water in the beginning of the freezing test for a day. The heave during the period of no access to the water was negligible (<0.3 cm) because of the low water content. After the sample had access to water, the frost heave for the image analysis sample was 1.45 cm and the reference sample 4.1 cm. In Figure 18, the temperature progress during the thawing cycle is presented for the image analysis sample and in Figure 19 the fully insulated reference sample. When the valve is opened, water at +4°C reaches the sample and due to capillarity reaches the frost front. Heat extraction from +4°C water thaws frozen area and ice lens formation initiates, see Figure 24.

The thaw and deformation progress is presented in Figure 20 for the image analysis sample and in Figure 21 for the reference sample. The frost depth for the reference sample is deeper compared to the image analysis sample at the beginning of the thaw cycle. The
thawing period is shorter for the reference sample, but frozen zones are noticed in the profile after the sample has thawed. Observed frozen zone after thawing was probably due to upward migration of melting water at 0°C in the sample. The temperature profiles presented in Figure 22 show the temperature along the sample and has a strong agreement.
with the observed frozen zones in Figure 21. The major part of the thaw settlements developed during the thawing phase for the image analysis sample, but only 20% of the deformation was developed in the reference sample. This deformation was calculated based on height including the frost heave. If a longer time perspective is considered, see Figure 23, the thaw settlements continue in the reference sample at a constant slow rate in a completely unfrozen sample showing the effect of consolidation. The frost heave in the
reference samples is approximately twice as large as for the image analysis samples. It is an
effect of insulation.

In order to have a better understanding of the progress, ice lenses are illustrated in Figure 26. It
shows how the ice lenses turned to water in a day and moisture redistribution in thawed soil. Light
gray area is the ice formation at the beginning of test 3 and dark gray area shows the formation of
ice lenses after a day of thawing in the schematic image.

3.4. Summary of the experimental observations
The frost heave in the reference samples is approximately twice as large as for the image
analysis samples. It is an effect of the opening for image analysis. The deeper frost depth
penetration results in thicker ice lenses (more heave) since the ice lens formation occurs closer
to the water source at the bottom of test equipment. The thaw deformations are larger for the
image analysis samples. The thaw deformation begins earlier for the image analysis samples
due to the opening in the insulation around the cylinder. The reference samples in test 1 and
test 2 shows similar frost depths and heave, while the image analysis samples have different
frost depth penetration and total frost heave. In all three tests, results from reference samples
show the same trend compared to those from image analysis samples. However, the amount
of settlement between reference samples and image analysis sample differs. Thawing of frozen
soil including ice lenses is faster in reference samples, see Figures 20 and 21. Discontinuous
area in Figures 20 and 21(between 10 and 15 hours) is believed to be due to the detection of 0°
C water.

It is expected that water drains downward in the soil due to the basic law of gravity. Although it
is observed that downward drainage exists, the majority of the water migration is upward. As it is
seen in Figures 8–11 from test 1 and explained in results, released water from ice lenses was
mixed with the fine particles from the top and sediment at the bottom of the voids generated by
ice lenses.

Test 3 was conducted without access to water at the beginning of the freezing test for a day.
Both the reference sample and image analysis sample had 10% of water content when they were
subjected to freezing temperature. The heave during the period of no access to the water was
negligible (<0.3 cm) because of the low water content. Frost heave to this moment was due to the
expansion of phase changing of in situ water. Since the water content was only 10% in the soil, the
expansion (frost heave) was very small compared to the sample with access to the external water,
i.e., tests 1 and 2. we didn't let the water into sample (from below as it is shown in figure 2), we
started freezing test without access to water (which is very important in freezing test). After 24
hours we opened the valves for the rest of the test (water access the way it is shown in figure 2).
The intention was to study the effect of external water on frost action. Water migrations were due to both capillarity and suction in the freezing soil. The water was sucked into the frost front and the color change within the soil was observed. The change of color in the sample proved the water migration in the soil. Soil is relatively darker when the water content is higher.

+4 degree water intake changing Thermal Equilibrium. As a result, the frost front will move (upwards, or downwards) to reach new equilibrium. This will be continued until new thermal equilibrium is reached and then frost penetration is continued downward again. Figure 25 shows the changes within the sample after a day showing the growing ice lenses as well as movement of 0°C isotherm line. As long as the heat extraction through the top cap is able to penetrate the frost depth in the sample again and IS able to freeze the newly sucked water, the frost front will continue to move upward.

At the latest stage of the freezing test, three different zones can be identified prior to the thawing test. The first picture to the left in Figure 26 shows these three zones. The first zone has the brightest soil which is a frozen part before water migration into the sample and shows the heat released from water access to the sample could not thaw it. The second zone’s soil is a bit darker than the first zone and it was frozen before access to water. The water thawed the second zone and froze again after heat extraction through the top cap. Higher water content in the second zone compared to the first zone makes the soil darker before and after freezing. The third zone is the rest of the sample which was not frozen before access to the water and the soil froze as it did in test 1 and test 2. The soil is darker from zone 2 due to the higher water content. Ice lenses were created in the sample similar to tests 1 and 2.

Prior to the thawing test, the frost depth penetrated to the depth of thermal equilibrium (7 cm). The warm temperature (+2°C) was applied through the top cap and the thaw front penetrated downward. Meanwhile, thick ice lenses started thawing as well as it is explained in the process for tests 1 and 2. The main difference is thawing in zones 1 and 2. Thawing in zone 1 has no visual change and settlements. When the thaw front reached zone 2, due to more released water in the voids, the water moved to the dryer parts in zone 1. This can be explained by capillarity in soil. It is because of the capillarity in soil, zones 1 and 2 have more of a uniform color than zone 3. Zones 1 and 2 contain roughly the same water content after 2 days and 10 h. When thaw front reached zone 3, thawing in ice lenses sped up while releasing water. Zones 1 and 2 got darker by time which means released water filled the voids in zones 1 and 2. This also means, similar to tests 1 and 2, water migration traveled upward. The volume of water was more than the voids, although the excess water which trapped in the soil was not as it was in tests 1 and 2. That is the reason that upward mudflow was not observed in test 3.

4. Discussion and conclusions on the thawing process
In this study, the thawing mechanism has been studied by image analysis. Figure 27 shows an idealized scheme of the observations in the result section of this study. It is a time, we apply warm
Temperature (+4) form the surface of frozen sample. Its beginning of thawing. Cycle is not necessary in this article, because we have only one cycle.

During the first stages of the thawing cycle, the thaw front migrates rapidly from the top downward until the thaw front reached the uppermost positioned ice lens, illustrated in Figure 27 as B. Simultaneously, the frozen zone thaws from below in a similar way.

At stage C in Figure 27, the ice starts to melt. During this process, the thaw front remains stationary. Depending on the initial saturation conditions of the tests, two different thaw progress schemes have been observed from this stage. The samples that were saturated during freezing, tests 1 and 2, follow the paths (D) and (E) in Figure 27 and the initially unsaturated sample, test 3, follows path (F) as the melted water can be absorbed by the soil body on top.

In samples with full access to the water (tests 1 and 2), released water from the ice lenses exceeds the void volume, i.e., the thaw rate exceeded the drainage capacity. Leslie and Bengt (1965) reported the formation of separated water sheets during these conditions. The water forms as water bubble and mudflow toward the surface of the sample as seen in Figure 27 (picture D and E). The driving force upward is probably the suspension of the fine particles in the upper part of the bubble and in combination with sedimentation in the lower part. The suspended soil in the water bubble migrates upward. The result is a redistribution of fine particles in the soil, which is in line with other studies, e.g. Chamberlain and Gow (1979).
During the thawing process, excess water dissolves finer soil particles in the soil matrix, see Figures 9, 10, 11 and 13. The zones of free water and suspended solids are unstable, and this results in loss of strength and stiffness. The response to an applied stress results in settlement and uneven soil surface. The arrival of the mudflow at the surface of the thawing soil has similar consequences as liquefaction.

Based on results from tests 1 and 2 in part of the thawed sample, soil behaved like a liquid. Therefore, the observed phenomenon in tests 1 and 2 can be explained by means of soil liquefying. A comparison between three tests indicates that soil should be relatively saturated during thawing in order to observe thawed soil liquefaction or fluidization. In test 3, the volume of water filled the void in dryer parts; therefore, the amount of released water was not enough to be trapped as it is observed either in test 1 or test 2.

In addition to the degree of saturation during thawing (volume of ice lenses), the thaw front penetration rate has a high impact on the mudflow. The faster the thaw front penetration, the higher the likely hood of soil liquefying. Test 2 was an example of the impact of the thawing rate. It was obvious that the volume of released water in test 2 was larger than those from tests 1 and 3.

For the test where the initial freezing was conducted under unsaturated conditions (test 3), the void space is sufficient to absorb the released water from the thawing ice lenses. It indicates that thaw weakening is dependent on the saturation conditions, which is in line with conclusions by Launonen and Turunen (1995) and Shoop et al. (2008).

Based on presented results and discussion following conclusions and remarks would be taken into consideration:

- If the soil gets oversaturated during thawing, free water including dissolved fine particles is formed in the thawed zone.
- The free water migrates upward as a mudflow and redistributes the soil particles.

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