Laboratory study of stone heave in till exposed to freezing and thawing

P. Viklander

Department of Civil and Mining Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden

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Abstract

Cyclic freezing and thawing of soils affect the structure and might, under certain conditions, cause stones and particles to move and relocate. The movement of stones will influence the soil structure and create weak and loose parts with increased permeability. This phenomenon has been known for a long time, but the knowledge regarding the magnitude of stone heave and soil conditions necessary for heave to take place has been lacking. Therefore, laboratory tests were carried out. Fine-grained till (moraine) was compacted to different void ratios and then saturated in a rigid wall permeameter which was exposed to one-dimensional freezing and thawing in a closed water system. The movements of an embedded stone were measured by an X-ray technique. Unfrozen samples, as well as samples frozen and thawed, were X-rayed and the stone movements were quantified after 1, 2, 4, and 10 cycles of freezing and thawing. The results show that stone movements (vertical and horizontal) take place due to freeze/thaw. The void ratio (the ratio of the volume of void space to the volume of solid substance in the sample) was found to be a key parameter for whether upward or downward stone movements took place. The downward movement occurred when the soil had a high void ratio, and the upward when the void ratio was small. In the loose soil, the stone first moved downwards and then, when the soil became denser due to freeze/thaw, it changed direction and heaved. In the loose soil, significant movements in the horizontal direction as well as rotation of the stone were also found. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: stone heave; freezing; thawing

1. Introduction

Freezing and thawing of soils can cause significant changes of the geotechnical properties. Studies of fine-grained soils (clay and silt) have shown that, due to freeze/thaw, the soil structure and thus the density and void ratio will change (Chamberlain and Blouin, 1978; Knutsson, 1983; Konrad, 1989; Nishimura and Ogawa, 1994; Eigenbrod, 1996) redistribution of water takes place (Skarzynska, 1985) the Atterberg limits are affected (Knutsson, 1984; Yong et al., 1985) and the strength, compressibility and pore water pressure upon thawing are influenced (Broms and Yao, 1964; Graham and Au, 1985; Eigenbrod et al., 1996). As a consequence of the affected microstructure, the permeability is changed, often by several orders in magnitude (see, e.g., Chamberlain et al., 1990; Yong and Haug, 1991; Benson and Othman, 1993; Othman et al., 1994;
Benson et al., 1995a and summarized by Viklander, 1995). Konrad (1989) has shown that changes in microstructure, in clayey silts, occur in the frozen part of the soil at temperatures lower than that of the warmest ice lens.

The microstructure is affected by the formation of ice lenses, expansion of the free water and the reduced amount of bound water. This effects will cause cracks to appear and particles to be redistributed (Chamberlain and Blouin, 1977, 1978; Othman and Benson, 1993; Benson et al., 1995b). Chamberlain and Gow (1979) and Taber (1943) have shown that polygonal vertical cracks are formed in clays exposed to freeze/thaw, and this cracking will contribute to an increased vertical water flow, i.e., an increased permeability.

However, little or no information is available regarding the effects of freezing and thawing on tills, even though this material is frequently used for construction in countries having been subjected to glaciation. Viklander (1998) showed that the permeability changed by a factor of 0.02–10 in a fine-grained till after 10 cycles of freeze/thaw. Depending on the void ratio (the ratio of the volume of void space to the volume of solid substance) before freezing, the permeability either increased or decreased after freezing and thawing. A residual void ratio was identified and it appeared in the soil after 1–3 cycles, representing a limit beyond which no additional volume changes took place by increasing the number of freezing cycles. The same residual value was reached independent of the initial void ratio, i.e., the void ratio increased when the initial void ratio was low and decreased if it was initially high.

In a coarse-grained material like till, general changes like those earlier mentioned take place and, in addition, particles will move, resulting in migration of fines, particle sorting and stone heave (Corte, 1961, 1962, 1963; Van Vliet-Lanoë and Pissart, 1984; Van Vliet-Lanoë, 1985). 

Migration of fines takes place when a thermal gradient is applied across a sample and causes freezing (Römkens and Miller, 1973; Goldenberg et al., 1993). It may result in a decreased permeability after thaw, as fines have a tendency to clog pores. Particle sorting takes place due to freezing and thawing, and will result in a stratified structure with individual layers with different permeability. Particle sorting has been described by Van Vliet-Lanoë (1985). Stone heave is caused by the ice-lensing process in frost-susceptible soils and results in a continuous moving of stones and coarse particles towards the cold end, i.e., normally the ground surface. The final result is well known, and is often noticed as local ‘bumps’ on paved surfaces, e.g., roads, streets, and parking places. In cultivated areas, stones are accumulated at the ground surface. When stones are moving upwards, the permeability of the adjacent soil will be influenced. Hydraulic barriers constructed of frost-susceptible fine-grained till might, therefore, be affected, resulting in a reduced function. Stone heave in an embankment dam may create cracks and fractures, which will act as flow channels initiating erosion and piping, especially if the filters are in poor condition. Thus, dam performance and safety will be negatively affected.

The purpose of this study was to detect stone movements in a fine-grained till by using a nondestructive testing method based on the use of X-rays. Furthermore, the movements were quantified and correlated to the initial conditions of the soil and to the microstructural changes.

2. Soil material and laboratory method

2.1. Soil material

The soil used in this study was a fine-grained, frost-susceptible till often used in Sweden as a hydraulic barrier in embankment dams and as top cover on waste landfills. Table 1 gives some geotechnical data.

2.2. Laboratory method

The movements of stones embedded in the fine-grained till were detected through X-ray techniques. Stones were artificially placed in samples, which were X-rayed before and after cycles of freezing and thawing.

Soil passing the 4.0 mm sieve was compacted into a plexiglass cylinder having a diameter of 52 mm and a height of 180 mm. The compaction work was varied between each sample, thus resulting in a soil matrix with different void ratios. At a distance of
Table 1
Characteristic of the fine-grained till

<table>
<thead>
<tr>
<th>Sandy silty till</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>$\rho_g^{max}$</th>
<th>$w^{opt}$</th>
<th>$\rho_s$ (t/m³)</th>
<th>$d &lt; 0.06$ (%)</th>
<th>$d_{10}/d_{60}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>49</td>
<td>26</td>
<td>6</td>
<td>2.06</td>
<td>6.3</td>
<td>2.66</td>
<td>34</td>
<td>96</td>
</tr>
</tbody>
</table>

a Average amount of each fraction obtained from several particle size distribution tests (by weight).

b Maximum dry density and optimum water content from compaction by modified Proctor method.

$\rho_s$ = Specific gravity.

d_{10}/d_{60} = Coefficient of uniformity.

90–130 mm from the bottom, a stone was placed. Its longest dimension was, at most, 25 mm and its shortest was at least 13 mm. The weight was 15–25 g. Above the stone, additional soil was placed and compacted to the same void ratio as the rest of the sample. The initial position of the stone was measured by a 0.1 mm sliding caliper and the X-rays. After compaction, the soil sample was saturated from the bottom, and was then frozen one dimensionally from the top down, in a closed system, i.e., the sample had no access to external water. The freezing took place in a freezing room at a temperature of −3°C and during freezing the cylinders were insulated by 50 mm polystyrene to obtain one-dimensional conditions. After freezing was completed, the samples were taken out into room temperature (+20°C) and were thawed. Then freezing started again. Frost heave and thaw settlement were measured by LVDT (Linear Variable Differential Transducer) and manual gauges.

In order to get a good contrast on the X-ray photos, between the stone and the surrounding soil, it

Fig. 1. An example of X-ray photographs of a loose sample (to the left) and a dense sample (to the right).
was found that the following values produced the best X-ray pictures: 87 kV and 18 A during 30 s. However, it was found to be difficult to separate an ordinary stone from the soil matrix when the X-ray pictures were analyzed. The difference in density was too small. Therefore, painted pieces of iron ore were used as embedded stones to get a better contrast, as a larger difference in density was obtained between the ore and the matrix soil, 3.5 t/$m^3$ compared to 2.2 t/$m^3$. In this way, the movements of the stones were followed without any problem.

The X-raying took place in two orthogonal directions, i.e., section A and B, after 1, 2, 4 and 10 cycles of freezing and thawing. During the X-ray procedure, the soil sample was placed horizontally on a table and was turned 90$^\circ$ between each exposure.

In order to have a fixed reference system to which the movements of the stone could be related, lead dots were fastened every 30 mm on the wall of the soil sample cylinder. The dots were all placed in the same section along the sample length. From initial calibration measurements, it had been established that measurements better than 0.1 mm could be taken on the X-ray photo, thus giving an accuracy of the stones movements better than ±0.5 mm.

Two typical X-ray pictures are shown in Fig. 1 representing a loose sample to the left and a dense sample to the right. The stone used in the loose sample was 22 mm and its contour is clearly visible as a dark area, with the surrounding soil being slightly lighter. The lead dots used for reference are also clearly visible. In the loose sample, the different soil layers can be seen as horizontal bands and in the dense sample, the contour of a natural stone is visible, located 5 mm above the lowest lead dot.

### 3. Results

The results presented here are the stones movements measured by the X-ray technique described. Two test series were carried out (PG1 and PG2), comprising 6 tests each. Table 2 gives the dry density ($\rho_d$), the void ratio before freezing ($e_0$) and after terminating each test ($e_{end}$), as well as the maximum number of freeze/thaw cycles ($N$). In addition, the evaluated movements of the stones are also presented in Table 2. As it was found that the stones are moving both vertically and horizontally, three typical numbers have been chosen to illustrate the movements, see Fig. 2. The numbers are:

- the net movement after 10 freezing cycles, presented as an average of the evaluated movements in sections A and B; $\overline{X}_{N=10}$
- the final vertical movement after 10 cycles, presented as an average of the evaluated movements in sections A and B; $\overline{X}_{N=10}^{vert}$
- the accumulated horizontal movement, presented as an average of the evaluated movements in sections A and B; $\sum\overline{X}_{hor}$

**Table 2** Data for the samples before and after freezing and thawing

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\rho_d$ (t/$m^3$)</th>
<th>$e_0$</th>
<th>$N$</th>
<th>$e_{end}$</th>
<th>$X_{N=10}^{net}$ (mm)</th>
<th>$X_{N=10}^{vert}$ (mm)</th>
<th>$\sum\overline{X}_{hor}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 1:1</td>
<td>2.12</td>
<td>0.25</td>
<td>10</td>
<td>0.25</td>
<td>4.0</td>
<td>2.5</td>
<td>20.5</td>
</tr>
<tr>
<td>PG 1:2</td>
<td>2.06</td>
<td>0.29</td>
<td>10</td>
<td>0.31</td>
<td>5.4</td>
<td>-2.8</td>
<td>9.5</td>
</tr>
<tr>
<td>PG 1:3</td>
<td>1.92</td>
<td>0.38</td>
<td>10</td>
<td>0.32</td>
<td>11.1</td>
<td>-11.0</td>
<td>15.8</td>
</tr>
<tr>
<td>PG 1:4</td>
<td>1.87</td>
<td>0.42</td>
<td>10</td>
<td>0.32</td>
<td>9.1</td>
<td>-7.3</td>
<td>13.5</td>
</tr>
<tr>
<td>PG 1:5</td>
<td>2.06</td>
<td>0.28</td>
<td>10</td>
<td>0.31</td>
<td>4.3</td>
<td>-0.5</td>
<td>6.8</td>
</tr>
<tr>
<td>PG 1:6</td>
<td>2.12</td>
<td>0.25</td>
<td>10</td>
<td>0.31</td>
<td>2.3</td>
<td>2.3</td>
<td>8.0</td>
</tr>
<tr>
<td>PG 2:1</td>
<td>1.70</td>
<td>0.56</td>
<td>10</td>
<td>0.34</td>
<td>2.7</td>
<td>-2.0</td>
<td>11.3</td>
</tr>
<tr>
<td>PG 2:2</td>
<td>1.70</td>
<td>0.56</td>
<td>10</td>
<td>0.33</td>
<td>11.4</td>
<td>-11.3</td>
<td>7.0</td>
</tr>
<tr>
<td>PG 2:3</td>
<td>2.16</td>
<td>0.23</td>
<td>10</td>
<td>0.29</td>
<td>1.3</td>
<td>0</td>
<td>6.8</td>
</tr>
<tr>
<td>PG 2:4</td>
<td>1.92</td>
<td>0.39</td>
<td>10</td>
<td>0.37</td>
<td>6.9</td>
<td>-1.3</td>
<td>9.0</td>
</tr>
<tr>
<td>PG 2:5</td>
<td>1.84</td>
<td>0.44</td>
<td>10</td>
<td>0.34</td>
<td>5.2</td>
<td>-4.3</td>
<td>8.5</td>
</tr>
<tr>
<td>PG 2:6</td>
<td>1.70</td>
<td>0.56</td>
<td>10</td>
<td>0.32</td>
<td>2.5</td>
<td>-2.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Evaluated movements of the stone are also given.

$\overline{X}$ = Average value of measurements in sections A and B.
Fig. 2. Definition of the evaluated movements after each cycle, the net movement ($\overline{X}_{N=10}$), the final vertical movement ($\overline{X}^\text{vert}_{N=10}$), and the accumulated horizontal movement ($\Sigma \overline{X}^\text{hor}_{N=10}$) after 10 cycles of freezing and thawing.

In Figs. 3 and 4, the evaluated vertical movement of the stone (mean value of sections A and B) is shown vs. the number of freezing and thawing cycles. Fig. 3 shows that both heave and settlement of the stone were found. Settlements in samples PG1:2, PG1:3 and PG1:4 and a small heave in PG1:1 and PG1:6 were noted, while no change in position was found in sample PG1:5. The movements were fully developed after two cycles in samples PG1:3 and PG1:4 while the other samples showed more variability. Similar results were found in tests PG2:1–PG2:6, but here only settlements were detected.

It should be emphasized that the irregular pattern in the movements shown in Figs. 3 and 4 are strongly influenced by the fact that the stones are not only moving vertically but are also moving horizontally and rotating. This behavior is clearly shown in Figs. 5 and 6 that show the stone movement in sample PG 1:6 and PG 1:3, respectively. The graphs illustrate the movements in an initially dense soil (PG 1:6) and initially loose soil (PG 1:3). The results from the 2 orthogonal sections, A and B, are separated and so is the position of the stone after a specific number of freezing cycles. The position of the stone prior to freezing is in the center of the graph in point (0, 0).

In Fig. 5, the movements of the stone in an initially dense soil sample (PG 1:6 having $e_0 = 0.25$) are shown. The unfilled symbols represent the position of the stone measured in section A, while the filled symbols are the corresponding positions in section B. After the first cycle, the stone moved 5 mm upward and 2.5 mm to the right. After the second cycle, it returned to its initial position and then again moved upwards. After 6 cycles, the stone was stabilized at a position 3 mm vertically above the starting position. A similar pattern of stone movements was found in section B. Thus, the net movement after 10 cycles was similar in both section A and B, despite large differences in the horizontal direction noticed during testing.

Fig. 3. The average vertical stone movements in samples PG1:1–PG1:6.

Fig. 4. The average vertical stone movements in samples PG2:1–PG2:6.

Fig. 5. Stone movements in sample PG1:6 having an initial void ratio of 0.25.
Fig. 6. Stone movements in sample PG 1:3 having an initial void ratio of 0.38.

From the X-ray photos taken in the two directions, it is clear that the stone not only is moving vertically but is also moving horizontally and rotating, thus explaining the differences in vertical movement between the two sections.

In Fig. 6, the corresponding stone movements in an initially loose soil (PG 1:3 having $e_0 = 0.38$) are shown. After the first cycle, the stone settled 7 mm and, at the same time, moved 7.5 mm horizontally to the right in section A. For following cycles, the stone turned to the left and finally stabilized 12 mm below its initial position. In section B, the net movement after 10 cycles was only vertical and downwards.

4. Discussion

The phenomenon of stone uplifting has been described in literature by several researchers (e.g., Beskow, 1930; Taber, 1943; Viborg, 1955; Kaplar, 1965; Ingles, 1965 and also summarized by Van Vliet-Lanoë, 1985). However, the stone heaving process is not yet fully understood nor explained; therefore, one purpose of this paper is to summarize the knowledge of today and to add further information from the tests performed.

In Fig. 7A–E, the stone heave process in a frost-susceptible soil is illustrated when the soil is exposed to one freeze/thaw cycle. The frost front propagates into the soil from the top, and at a specific time the frost front is located just above the stone (Fig. 7A). Pore water is sucked from unfrozen soil beneath towards the growing ice lens and thus through the frozen fringe. After some additional freezing (Fig. 7B), the frost front moves further down, and a cavity is created above the stone due to frost heave of the overlaying soil (Kaplar, 1965). The stone maintains its original position as long as the stabilizing force, i.e., the self-weight of the stone and the boundary cohesion between the unfrozen soil and the stone, is greater than the lifting force originating from the adfreezing between the stone and the frozen soil. As soon as the lifting (adfreezing) force is larger than the force keeping the stone in place, the stone will heave. The stone will also heave if an ice-lens is formed beneath it. This process is illustrated in Fig. 7C. As a consequence of the stone movement, a cavity is created immediately below the stone, and this cavity will increase in size as long as the frost heave conditions are prevailing. Due to the negative
pressure in the pore water adjacent to the continuously growing ice lenses, water will be transported upward and pass the created cavity, which will gradually fill with water. The frost front propagates further, and the water in the cavity will turn into ice. Fig. 7D shows the partly ice-filled cavity below the stone and at this phase the heaving of the stone has ended and the frost front is located below the bottom of the ice-filled cavity. At this stage, the frost heave will continue, but the growing ice lenses are now located below the stone; therefore, the relative position of the stone to the ground surface will not be changed.

When the temperature rises, the thaw front propagates from the top downwards. The thermal conductivity in the homogenous stone is higher than that in the surrounding soil, typically 3.8 W/m K compared to 2.0–2.5 W/m K (Andersland and Ladanyi, 1994) depending on porosity, degree of water saturation, and mineral. The thaw front will, therefore, penetrate through the stone faster than through the surrounding soil where, in addition, ice has to be melted. The ice in the cavity below the stone will consequently start to melt before the soil around it thaws. The stone will, therefore, be kept in the uplifted position when the ice in the cavity melts (Fig. 7E). During thawing of the surrounding soil, water and small soil particles will move downward due to gravity, through fissures and openings between the stone and the matrix soil. Particles, therefore, accumulate, in the big, previously ice-filled cavity; consequently, the stone is prevented from returning to its original position.

Beskow (1930) proposed a slightly different explanation to the stone heave phenomenon. He suggested that the walls of the cavity can cave in during thaw, thus filling the cavity with fines; this idea was also adapted by Viborg (1955). Viborg emphasized the importance of the accumulated water beneath the stone, and the fact that the pore wall can soften up and larger particles can loosen and fall into the cavity. It is the author’s opinion that this behavior might be most realistic in slurries, but can probably also occur in thawing ice-rich soils.

From this, it is understood that the cavity does not necessarily have to be completely filled with particles in order to prevent the lifted stone from returning to its original position. Neither will the material in the filled cavity get the same dry density as the surrounding soil; normally it will get a smaller dry density, thus a higher void ratio.

In addition to the described process, some additional processes may lead to movements of stones and embedded objects. In a soil with a loose structure, consolidation may take place due to the freeze/thaw cycles. Thus, the embedded stone will move downwards. However, if the freeze/thaw cycles are repeated, the loose soil structure will eventually reach its residual void ratio, as was pointed out by Viklander and Knutsson (1997). At this stage, the stone heaving starts again, when the soil is subjected to new freezing cycles. The movement pattern of objects in a frost-susceptible soil; therefore, depend on the initial void ratio of the soil. If this ratio is small, the objects are lifted continuously, from the first freezing and thawing cycle, while in a loose soil the objects might first move downwards but, after a number of freezing cycles, start to move in the opposite direction.

In permafrost areas, stones may heave due to a process known as ‘frost-push mechanism’ (Washburn, 1979). It takes place when freezing proceeds from the bottom up, i.e., when the active layer is frozen from beneath and stones are pushed upward due to the freezing. This process will not be discussed here.

The recorded movements of the embedded stones are relatively small, not exceeding 12 mm in any of the tests (see Figs. 3 and 4). These small movements, also after 10 freezing and thawing cycles, are due to freezing that occurred under closed conditions, with no external water available. If freezing were carried out in an open system, more intense ice-lensing, and thus frost heave, would have taken place. This open water system would also increase the movements of the stone. In all the tests, the movements were stabilized at the final level after 2 to 3 freezing and thawing cycles, even though some scatter in recorded movements appear. The scatter is most pronounced when the stone is heaving.

In Figs. 8 and 9, the vertical movements, after 10 freezing cycles, are plotted vs. the initial void ratio of the soil. The two sections A and B are separated. Fig. 8 clearly shows how the stone heaves when the surrounding soil has a low initial void ratio (a dense soil), while the resultant movements are downwards when the soil has a high initial void ratio (a
loose soil. This influence of void ratio supports the idea that the initial void ratio of the soil is a key parameter for whether a stone heaves or settles. A critical void ratio can be identified when neither heave nor settlements occurs. From Fig. 8, this critical void ratio can be estimated to be 0.30. The same pattern in the movements can be found in Fig. 9 which shows the resultant movements in the tests PG 2:1–PG 2:6. In these tests, the initial void ratios were higher than those in series PG 1. This loose soil structure explains why no or small vertical movements are present. In most tests, the void ratio was too high to cause lifting; instead, settlement of the stone took place. The critical void ratio is, therefore, harder to evaluate from this test series, but one can argue that it seems to be close to 0.30. In Fig. 9, some very small settlements are shown for void ratios as high as 0.56 (PG 2:1 and PG 2:6). In test PG 2:1, the stone moved more horizontally (11.3 mm) than vertically (down 2.0 mm) (see Table 2). This movement indicates that, when the void ratio is high, objects will move due to freezing and thawing but not always vertically. The direction is probably influenced, to a high degree, by local inhomogeneous parts of the soil, and these are more pronounced in loose soil than in dense. The stone in test PG 2:6 did not show very much movement in any direction, neither vertical nor horizontal (down 2.5 mm and horizontally 5.5 mm). However, the soil itself behaved in the expected manner. As the soil had an initial high void ratio, it consolidated and its void ratio was, after all the freezing cycles, 0.32 (see Table 2). This value of void ratio is in accordance with the idea of a residual void ratio as pointed out by Viklander and Knutsson (1997). It is, therefore, not yet understood why the stone moved such a small distance in this single test.

Fig. 10. shows all the data from Figs. 8 and 9 in one graph. An obvious trend can be seen, with recorded heave when the void ratio is small and settlement of the stone when the void ratio is high. The two exceptions for void ratio of 0.56 are discussed earlier. The critical void ratio when the stone shows neither heave nor settlement is in the range of 0.28–0.34. This range of void ratio is close to the void ratio the samples obtain after 10 freezing and thawing cycles (see Table 2). This finding supports the idea that a residual void ratio exists in a soil subjected to cyclic freezing and thawing (see Viklander and Knutsson, 1997).

Fig. 11 shows the net movement of the stone in each test vs. the initial void ratio of the soil. As described in Fig. 2, this net movement also includes a horizontal component. Fig. 11 demonstrates that the displacements of the embedded stones increase with increasing void ratio, thus indicating that the
stones move considerably both vertically and horizontally due to freezing and thawing. Note that net movements occur at void ratios close to the earlier mentioned critical value, around 0.30. At this void ratio, the stones are not moving vertically, but obviously they are displaced horizontally. Several factors are important for the stone heave process: (1) type of soil, (2) temperature gradient, (3) water conditions, (4) type of stone, (5) shape of the stone, (6) direction of the stone, and (7) location of the stone.

The type of soil is important, especially its degree of frost-susceptibility and density. In a highly frost-susceptible soil, stones move more compared to what happens in a non frost-susceptible soil. This difference is simply related to the magnitude of frost heave. However, an exception exists: Corte (1961) showed that objects buried in a saturated, clean, non-frost-susceptible sand might be lifted due to freeze/thaw. In the tests presented here, a frost susceptible fine-grained till was used and stone movements were detected, even though the movements were not always large. The amount of water available and the scale effects—the relation between the stone size (maximum 20 mm) and the cylinder diameter (52 mm)—might influence the measured deflections.

The temperature gradient controls temperature regime in the samples. If the temperature gradient is optimal, the stone can heave vertically as much as the soil heaves. Thus, the largest possible cavities are created and the maximum stone heave might appear. However, if the gradient is too great, the soil freezes too fast, the stone will be trapped into the frozen soil matrix, and no cavity will grow beneath it. In the presented tests, the temperature gradients were not always optimal and the frost front passed the stones too fast in some of the tests. However, the author feels that, despite the varied temperature gradients, the recorded movements gave a good picture of the stone heaving process.

The water conditions are of utmost importance, simply because water has to be present in order to form ice and create frost heave. In the described tests, freezing took place under closed conditions; therefore, the amount of available water was limited. The heave of the stones was, therefore, restricted. However, the tests show that even if the amount of available water is small, stones move due to freezing and thawing. If water is easily available, the heaving will be larger.

The type of stone (e.g., granite or shale) seems to be of minor importance, as all stones of appropriate weight and size can be lifted due to freeze/thaw. However, the thermal conductivity in stones can differ, and this difference will have an influence on the thawing of the ice in the cavities created below the stone. Archeological investigations have shown that objects such as bones, quartz tools, and other artifacts are distributed in the vertical direction in soil profiles due to heaving caused by freezing and thawing (Broadbent, 1979). Thus, independently of whether the surface of the objects are rough or smooth, they will be lifted anyway. The weight of artifacts seems to have some importance as objects heavier than 50 g or more were located on deeper levels, whereas the smaller objects had moved upward.

The shape of the stone, its size, its orientation in relation to the heat flow and its depth below the soil surface have been found to influence the uplifting behavior significantly. According to Taber (1943), stones which are wedge-shaped downward as well as tubular or elongated normal to the soil surface will be most easily lifted. Stones that are rounded (spheres), wedge-shaped upward or elongated parallel to the soil surface are not so easily lifted because the soil above these types of stones heaves, and an unfilled void is created above them. Thus not enough adfreezing force can be mobilized to lift the stone. Tests by wood pegs have shown that the deeper the insertion depth is, the greater heave is noticed, as long as the insertion depth did not exceed the depth of the frost (Washburn, 1979). Thus, if a tabular...
stone is located perpendicular to the surface, it can heave and the cavity created will be bigger the longer the stone is. In the actual tests, the stones were fairly rounded with a ratio between the longest and shortest axis of between 0.60 and 0.72.

The direction of stones is important. The freezing process tends to make tabular stones become oriented perpendicular to the surface after repeated cycles of freezing and thawing (Taber, 1943). Also, ordinary stones tend to be oriented with the long axis parallel to the heat flow. In addition, according to Washburn (1979), cylindrical objects oriented normal to the freezing front move upwards faster than spherical objects.

The location of a stone relative to the soil surface controls the magnitude of heave. This factor is, of course, closely related to the temperature gradient. The location of a stone is important because, at a certain depth below surface, the heave process presented in Fig. 7 is not valid any more. The heave may then instead be caused by the growth of ice needles (pipkrake) beneath the stone (Van Vliet-Lanoë, 1985). Ice needles can be formed parallel to the temperature gradient and range in length from a few millimeters to as much as 35–40 cm (Washburn, 1979). They are capable of lifting boulders. This phenomenon is, however, most common at shallow depths.

Viborg (1955) has explained the segregation, i.e., the accumulation of sand and gravel beneath big stones. At freezing, when the cavity is created beneath the stone (Fig. 7C), the adjacent soil is moistened, due to the suction at the freezing front. Coarse particles in the walls of the cavity fall more easily down to the bottom of cavity than smaller ones, thus segregation occur.

The effective heave rate for stones is thus dependent on many factors. From visual observations on parking sites and roads in northern Sweden, a heave rate of 1–5 cm/yr can be estimated. Broadbent (1979) calculated an average heave rate of objects (artifacts) found in an archeological investigation to be 0.057 mm/yr. The result from this study shows that the upward stone movement rates varied between 0 and 10 mm per freeze/thaw cycle, and that the horizontal movements were in the same range.

Finally, some critical judgment of the X-ray tests will be discussed. As mentioned, the tested stones were found to move both vertically and horizontally when exposed to freeze/thaw. Therefore, it was sometimes difficult to interpret the X-ray photos as some of the stones also rotated. However, by using a 3-D plotting device, when analyzing the results, or by using tabular stones instead of sub-rounded, as in this study, one will probably get a correct picture of the stone paths more readily.

5. Conclusions

Stone movements (vertical and horizontal) in a fine-grained till (moraine) exposed to a maximum of 10 cycles of freezing and thawing were measured by X-ray techniques. The method worked well, even though significant improvements can be made in order to avoid the uncertainty related to angular distortion.

The stones moved vertically upward (heaved) in samples with different void ratios, ranging from 0.25 to 0.56. For low void ratios (dense soil), the stones heaved due to the cyclic freezing and thawing, while the stones moved vertically downward (settled) in samples with high void ratio (loose soil). The void ratio was found to be a key parameter for whether the stones heaved or settled.

A critical void ratio, at which neither heave nor settlement took place, was found. For the till studied, this ratio was in the order of 0.30.

The void ratio after freezing and thawing approached a residual value, in the range of 0.29–0.34. This finding supports the idea that a residual void ratio exists in a till after freezing and thawing. A soil with a low initial void ratio will become looser, and its void ratio will approach the residual value, while the initially loose soil, with a high void ratio, will become denser and the void ratio will also approach the ultimate residual value.

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