Effect of freezing and thawing on soil permeability: newly equipment and experimental results

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Abstract. In a cold climate design of dams, clay barrier liners on landfills, and structures on frost-susceptible soils is a challenge for geotechnical engineers. During service life of the structures a frost heave may reach 15-20% of the depth of a frost penetration and an uplift movement are accompanied by the formation of layered or lattice cryogenic texture. When thawing, macro- and micropores are formed instead of ice lenses. Basically pores are oriented predominantly along frost front. They are a reason of horizontal water permeability increase, consequently, reduce of stability of the slopes and decrease of the effectiveness of the landfill clay barrier liners. The paper presents a new apparatus for studying water permeability and frost heave of soils which allows to carry out horizontal or/and vertical permeability tests (along and across layered cryogenic texture) after assigned number of freeze-thaw cycles without withdrawal of a soil sample from apparatus. The results for clay and fine sand samples are obtained. Clay and fine sand samples showed an increase of horizontal hydraulic conductivity after 2 - 4 freeze-thaw cycles. Relationship between water flow velocity and hydraulic gradient for non-Darcian and Darcian flow is obtained as a result of vertical permeability tests of clay samples in unfrozen state.

1. Introduction

Compacted clay barrier liners are used to isolate municipal and industrial waste landfills in cold climate. The disadvantage of these liners is its frost-susceptibility. Frost heave may reach 15-20% of the depth of frost penetration and uplift movement are accompanied by the formation of ice lenses in the frozen soil, in other words, layered or mesh-like cryogenic texture is appeared. When thawing large pores are formed instead of ice lenses. Mainly large pores are oriented predominantly along frost front. They are a reason of permeability increase [1] and, consequently, decrease of the barrier protective properties. Besides, possible phenomenon of permeability anisotropy of the clay barrier liners should be taken into account.

Frost heaving process is itself usually studied on cylindrical samples, which are frozen from top to bottom, and with free water intake through sample bottom. Water permeability tests are mainly carried out along sample in upstream flow after assigned number of freeze-thaw cycles of samples.

In the apparatus of E.J. Chamberlain, A.J. Gow et al. [2] a clay sample was put in a transparent thick-walled cell of diameter 63.5 mm with a teflon cover. Tests for frost heave started after consolidation was completed. The frost front rate was maintained by variation of the temperature at
the top and bottom plate and amounted to 5 mm/hour. Thawing of the sample was carried out at temperature 22°C. After the assigned number of freeze-thaw cycles water permeability was determined by the following way: water was injected through porous stone at bottom plate and was discharged through the porous plate in the piston placed on top of sample. The apparatus permitted determining water permeability at vertical direction, i.e. across to layered cryogenic texture. Experiments showed that hydraulic conductivity of clay at overburden pressure up to 14 kPa became in 10-100 times as much after 5 freeze-thaw cycles. Further growth of hydraulic conductivity was not significant: after 15 freeze-thaw cycles it became in 1.5-2 times as much as compared to the values obtained after 5 cycles (figure 1).

Figure 1. Effect of freeze-thaw on hydraulic conductivity of clays [5].

Similar results were also obtained later by others researchers. To evaluate changes of hydraulic conductivity experiments were carried out by C.H. Benson and M.A. Othman [3] in terms of freeze-thaw in the field with glacial clay (LL=32%, PI=14%) compacted in a large PVC tube (diameter 300 mm, height = 910 mm). After freeze–thaw sample was extracted and cut into horizontal sections and standard permeability test was implemented under overburden pressure 34 kPa and hydraulic gradient 10. The results of experiment showed 40-80 times increase of hydraulic conductivity after 2-4 cycles of freezing as compared to the input values.

T.F. Zimmea and C. La Plante [4], W.-H.Kim and D.E. Daniel [5] investigated the effect of water content on the water permeability after assigned number of freeze-thaw cycles. It appeared that hydraulic conductivity of clay became 2-4 times as much and 50-200 times as much after 5 freeze-thaw cycles for compacted dry of optimum and wet of optimum water content respectively.

According to J.-M. Konrad and M. Samson [6] hydraulic conductivity of silty clay (LL=42%, PI=19%) after freeze-thaw in 2-40 times as much as before freezing. Tests were carried out in consolidometer consisting of a plexiglass cell, loading frame equipped with displacement sensors and the system of cooling/heating of the sample. Water permeability as in the quoted above papers was measured only in vertical direction. Tests were implemented on the samples consolidated under overburden pressure 60...460 kPa. Sample freezing was carried out at constant vertical pressure and temperature from minus 2 °C to minus 10 °C. The researchers developed a quantitative model for predicting the hydraulic permeability of post-thawed soils based on the changes in void ratio.

Special apparatuses were created for investigation of water permeability in the direction along frost front. In the apparatus of V.N. Zhilenkov [7] a sample with a diameter of 18 cm is placed in a coaxial chamber with porous walls. In the center of the chamber perforated tube is placed. Soil sample are frozen from up to down, overburden pressure are applied through an annular piston. After consolidation the soil sample is frozen and thawed under assigned number. Hydraulic conductivity in the radial direction (from perforated tube to the porous walls of chamber) are determined. The disadvantages of the apparatus are a difficult preparation of soil sample with axial hole and its friction in contact with chamber wall and perforated tube.

The freeze-thaw permeability test system of G. Hirose and Y. Ito [8] allows soil testing by two methods. In the 1-D test the load is applied vertically, frost front and water flow are also moved vertically. In H-test the load is applied vertically but the specimen is frozen horizontally and permeability test is performed in vertical direction. The second method is used to study the processes
that occur around freezing pipes in frozen soil structures under artificial ground freezing. The tests were carried out at a rather high pressure, up to 500 kPa, and the sample was frozen at a temperature gradient of 0.6–0.7 °C/cm. It should be noted that moving the frost front in the horizontal direction does not reflect the process of soil freezing in earth structures such as – barrier liners, dams, fills, etc [9].

The objective of the research is studying water permeability of frost-susceptible soils in terms of water flux along and across the frost front by using newly developed laboratory apparatus.

2. Materials and Methods

2.1. Laboratory test apparatus

The authors of this article designed and the GEOTEK Ltd (Russia) manufactured an apparatus for studying water permeability and frost heaving of soils (figure 2). A cylindrical sample of standard sizes is tested in the apparatus: with a diameter of 100 mm and height of 150 mm or more [TC-216, ISSMGE]. The load is applied vertically on a top plate and frost front is moved from top to bottom. After thawing water permeability test is performed in the radial and axial directions. The most noticeable distinction apart from above apparatuses is that permeability test is carried out in radial direction through perforated walls of cell before and after freeze-thaw process [10, 11].

The cell consists of three identical acrylic sectional rings with height of 65 mm. The walls of the rings are double, the space between the walls are divided into four sectors. Two sectors with perforated internal walls is used for performing head permeability test, the other two with non-perforated walls - for placing tubes for water supply and removal of water and air.

![Figure 2. Apparatus used for measure hydraulic conductivity and frost heaving susceptibility: (a) is photo; (b) is scheme; 1 - base; 2 - soil sample; 3 - tubes for water drainage and supply; 4 - perforated inner walls; 5 – acrylic ring; 6 - supply tube.](image)

For freezing the soil sample the water from rings is drained, water is available free only through porous disk at the bottom base plate. Water supply from the reservoir is carried out through the inlet port on the sample base plate with flexible plastic tube. Temperature sensors are installed by pushing into soil sample to its center through holes drilled in joint of rings. Outside, the cell is protected by a thermal insulation material (figure 3). Overburden pressure (if needed) are applied through a cooling/heating piston located at the top of the soil sample.

When freezing the temperature is maintained at top of the soil subject to the availability of providing the frost front penetration rate in the soil sample equal to rate in field conditions (≈10-20 mm/day) and temperature of sample top is varied from minus 3.5 °C to minus 4.5 °C. The temperature of the sample bottom is maintained within 1.5…2.5 °C. The soil sample are frozen from top to bottom. The uplift deformations are measured by displacement transducers. When water moves from bottom
part of a sample to the frost front and freezes, frost heave occurs for frost-susceptible soils. The phenomenon is accompanied by uplift of piston and disclosure of joints of the rings.

![Figure 3. Frost heave test.](image1)

![Figure 4. Horizontal permeability test.](image2)

After freezing soil sample down to 100...120 mm the antifreeze agent circulation in piston is stopped and the temperature is gradually raised to thaw the soil sample. Immediately after thawing a difference in the total heads equal to $\Delta H = (H_1-H_2)$ (figure 4) is applied to one of the cells providing horizontal water flow by opening the corresponding taps. For assigned hydraulic gradients, the water permeability of the soil sample is determined. The experiment is repeated after 2 days. The changes of

![Figure 5. Vertical permeability test.](image3)
hydraulic conductivity can occur because of collapsing of macro – and micropores in soil. Further the soil sample without removing from the cell, is frozen again and procedure is repeated assigned number of cycles.

Using the same sample, water permeability in vertical direction may also be studied (figure 5). For this, after freezing a plate with a porous disk is mounted on top of the soil sample, a difference in the total heads is created to provide water flux from lower to upper direction and water permeability test is performed. For clays permeability test can be carried out with using one or two acrylic rings.

2.2. Determining the cell parameter at horizontal permeability test

Due to the variable cross-sectional area of the water flow and uncertainty of water flow paths in the soil sample when horizontal permeability tests performed, it is necessary to determine the constant parameter allowing to define hydraulic conductivity of soils. For such parameter the ratio of the cross-sectional area \( A \) and length of water flow path \( l \) may be taken, which is determined by the results of permeability test of the soil with a known hydraulic conductivity. To determine the parameter \( A/l \) a series of constant head permeability tests was carried out and hydraulic conductivity for medium sand (dry density was 1.65 g/cm\(^3\)) was determined which was equal to 5.5 m/day. Taking into account a water discharge \( Q \) at assigned difference in the total heads \( \Delta H \) and hydraulic conductivity of soil sample the constant cell parameter was determined by Darcy’s law. For test soil sample cell parameter was equal to 2.99. The experimental results are presented in table 1.

| \( Q \), cm\(^3\)/s | \( \Delta H \), cm | \( A/l \), cm |
|-----------------|---------------|--------------|
| 0.103...0.124   | 6             | 2.98         |
| 0.072...0.078   | 4             | 2.93         |
| 0.035...0.043   | 2             | 3.07         |
| **Average**     |               | **2.99**     |

To verify the cell parameter, numerical modeling of permeability tests was performed in the PLAXIS 3D. A finite element (FE) model with \( 1 \times 10^5 \) 15-node elements is presented in figure 6 (a). To prevent free seepage through the sample surface the model was “covered” by a waterproof membrane. Water flow boundary conditions assigned as total heads \( (H_1 \) and \( H_2) \) were only applied to holes on sample surface. According to the results of FE simulation of steady-state water flow in fully-saturated soil (figure 6 (b)) the water discharge at a total head difference of 6 cm was 0.111 cm\(^3\)/s, at 4 cm - 0.074 cm\(^3\)/s, and at 2 cm - 0.037 cm\(^3\)/s. The calculated ratio \( A/l \) was equal 2.91 what have a good agreement with the results of permeability tests.

2.3. Soil material

Physical characteristics of the studied soils: clay (CL-ML) and fine sand (S-SM) are shown in table 2. Glacial clay undisturbed samples were taken in one of the areas of the Arkhangelsk region. Sand is solid waste of mineral ore dressing of one of the mining enterprises in the region. Disturbed samples of fine sand were compacted to assigned dry density and water content for permeability testing.

2.4. Water permeability and frost heave tests

Study of water permeability of clay and fine sand samples were carried out in two stages. At the first stage experiments were performed for unfrozen soils in terms of upstream water flow according to figure 5. Hydraulic gradients varied from 2 to 15 for clay and from 1 to 10 for sand. The load on the top of the soil sample is not applied.

At the second stage experiments were carried out after freezing-thawing according to figure 4. Initially soil samples were frozen to 100-120 mm depth (figure 3) with frost penetration rate equal to \( \approx 10-20 \) mm/day. Frost heave of samples were measured. Then samples were fully thawed and permeability test was performed. In two days the test was repeated. So hydraulic conductivities in one
hour and two days after freeze-thaw cycle was determined. Then soil sample was frozen again and the
procedure was repeated three times. The load on the top of the soil sample is equal to the weight of the
cooling/heating piston.

![Figure 6. Finite Element model in PLAXIS (a) and Water flux within cell (b).](image)

### Table 2. Properties of soils.

| Soil       | Clay (CL-ML) | Fine Sand (S-SM) |
|------------|--------------|------------------|
| $\rho_s$, g/cm³ | 2.69         | 2.68             |
| W, %       | 19           | 21               |
| $\rho$, g/cm³ | 2.01         | 1.92             |
| Void ratio | 0.59         | 0.69             |
| PI         | 8            | -                |
| LL, %      | 21           | -                |
| Percentage of sand, % | 55.45 | 95.74 |
| Percentage of silt, % | 23.85 | 3.24 |
| Percentage of clay, % | 20.70 | 1.02 |

3. Results

It is known that water flow in clays can be described by Darcy’s law but linear relationship between
flow velocity and hydraulic gradient has a good correlation only for hydraulic gradient which exceed
threshold gradient. For gradients less than critical gradient the relationship becomes non-linear[12].

S. Hansbo [13] pointed that water flow velocity is proportional to a power function of hydraulic
gradient when the gradient is less than a critical value. He proposed a relationship between water flow
and hydraulic gradient to consider the non-Darcian flow in clays:

$$q = K \cdot i^n$$  \quad \text{for } i \leq i_1 \quad (1)
$$q = K \cdot i^n \cdot (i - I)$$  \quad \text{for } i \geq i_1 \quad (2)

$$i_1 = \frac{I \cdot n}{(n-1)}$$  \quad (3)

where $K$ - hydraulic conductivity, $i$ - hydraulic gradient, $n$ - exponent of exponential flow at low
gradients, $i_1$ - modified hydraulic gradient, $I$ - threshold gradient which is defined as intersection
between the $i$ axis and linear part of relationship $q = K \cdot i$. The complication is necessity to determine
parameter $n$ by the iteration method.

D. Swartzendruber [14] proposed to define water flow velocity according to the following relationship:

$$q = K \left[ i - I \left( 1 - e^{-\frac{i}{I}} \right) \right]$$  \quad (4)

where $K$ is hydraulic conductivity, $I$ is threshold gradient and $i$ is hydraulic gradient.

Results of water permeability tests of clay for unfrozen state in upstream water flow showed that
hydraulic conductivity is equal to $2.42 \times 10^{-8}$ cm/s and hydraulic threshold is 5.73. Properties of clay
are presented in Table 2. A linear relationship between water flow and hydraulic gradients (Darcy’s law) is observed at gradients exceeding hydraulic threshold by 1.2..1.3 times. Non-Darcian flow below threshold gradient is occurred. (Table 3).

We propose the following relationship between water flux and hydraulic gradient for non-Darcian (6) and Darcian flow (7):

\[ q = K \cdot I \cdot A(\exp(bI) - 1) \quad \text{for } i < i_2 \] (5)

\[ q = K(i - I) \quad \text{For } i \geq i_2 \] (6)

where \( K \) is hydraulic conductivity, \( I \) is threshold gradient and \( i \) is hydraulic gradient, \( i_2=1.25\cdot I \), \( A = 0.005; B = 3.124/I \).

Relationships between water flow velocity and hydraulic gradient for clay are presented at figure 7. It should be noted that Swartzendruber’s relationship is less accurate for gradients below threshold gradient, while Hansbo’s relationship and relationship of ours have a good agreement with experimental values of water flux.

![Figure 7. Relationships between water flow velocity and hydraulic gradient.](image)

Results of water permeability tests after assigned freeze-thaw cycles for clay and fine sand are presented in table 3. Hydraulic conductivity of clay after freeze-thaw cycles varies from \((1.03…1.20) \times 10^{-5}\) to \((7.21…7.35) \times 10^{-6}\) cm/s. Threshold of hydraulic threshold is \(2.99…5.20\). Hydraulic conductivity of sand is \((0.71…0.75) \times 10^{-3}\) cm/s.

Results of frost heave test showed that clay and fine sand are frost-susceptible. The heave strains defined as ratio of frost heave to frost penetration depth are 0.036 and 0.035 for clay and fine sand respectively.

| Soil   | Parameter | Before freezing | Number of Freeze-Thaw cycle |
|--------|-----------|-----------------|----------------------------|
|        |           |                 | after 2 cycle              | after 3 cycle              | after 4 cycle              |
|        |           |                 | in 1 hour | in 2 days | in 1 hour | in 2 days | in 1 hour | in 2 days | in 1 hour | in 2 days |
| Clay   | \( K, \) cm/s | 2.42 \( 10^3 \) | 1.03 \( 10^3 \) | 7.23 \( 10^6 \) | 7.35 \( 10^9 \) | 1.18 \( 10^3 \) | 7.21 \( 10^6 \) |
|        | I         | 5.73            | 3.17      | 5.14      | 2.99      | 5.01      | 3.10      | 5.20      |
|        | B         | 0.55            | 0.99      | 0.61      | 1.04      | 0.62      | 1.01      | 0.60      |
|        | \( i_2 \) | 7.16            | 3.96      | 6.43      | 3.74      | 6.26      | 3.88      | 6.50      |
| Fine Sand | \( K, \) cm/s | 0.5 \( 10^3 \) | 0.71 \( 10^3 \) | 0.71 \( 10^3 \) | 0.75 \( 10^3 \) | 0.73 \( 10^3 \) | 0.74 \( 10^3 \) | 0.73 \( 10^3 \) |
4. Discussion

Results of water permeability tests showed that hydraulic conductivity and hydraulic gradient of clay and fine sand are changed after assigned number of freeze-thaw cycles as in unfrozen state (figure 8).

After the first two freeze-thaw cycles in one hour following in fully thawing hydraulic conductivity of clay is increased from \(2.42 \times 10^{-8}\) to \(1030 \times 10^{-8}\) cm/s, than in two days it slightly decreased to \(723 \times 10^{-8}\) cm/s. After next freeze-thaw cycle hydraulic conductivity is increased to \(1200 \times 10^{-8}\) cm/s and then decreased to \((721...735) \times 10^{-8}\) cm/s. Further process of freezing-thawing practically haven’t an effect upon hydraulic conductivity. The opposite phenomena is occurred for the threshold gradient \((I)\) which is decreased from 5.73 to 3.17 after first two freeze-thaw cycles and then increased to 5.01...5.20 after each next freeze-thaw cycles. So the threshold gradient of clay is become close to values in unfrozen state.

Hydraulic conductivity of fine sand after 2-4 freeze-thaw cycles when fully thawed is increased from \(0.5 \times 10^{-3}\) to \((0.71...0.75 \times 10^{-3}\) cm/s) and threshold gradient isn’t occurred.

Changing of water permeability of clay is explained by existence of pores (micro- and macropores) which have appeared as a result of processes of formation of ice lenses which are mainly oriented horizontally i.e. along frost front (figure 9). After thawing of ice the pores are being collapsed slowly what is resulted in changing hydraulic conductivity and threshold gradient. Besides residual micro-, macropores and other forms of secondary porosity caused by frost heave of soils can contribute to increasing of water permeability.

![Figure 8. Relationship between water flow velocity and hydraulic gradient for clay (a) and fine sand (b).](image)

![Figure 9. Cross-section of clay immediately (a) and in 2 days after thawing (b).](image)

5. Conclusions

Designed and manufactured apparatus for studying water permeability and frost heave of soils is allowed to carry out horizontal or/and vertical permeability tests (along and across layered cryogenic
texture) after assigned number of freeze-thaw cycles without withdrawal of soil sample from apparatus.

Results of frost heave test showed that clay and fine sand are frost-susceptible. Heave strains are 0.036 and 0.035 for clay and fine sand respectively.

Results of water permeability tests showed that hydraulic conductivity and hydraulic gradient of clay and fine sand are changed after assigned number of freeze-thaw cycles as in unfrozen state. The hydraulic conductivity of clay after freezing-thawing is equal to \((7.21 \ldots 7.35)\times 10^{-6}\) cm/s what is in 3 orders of magnitude more than in unfrozen state. The threshold gradient isn’t practically changed and varies from 5.01 to 5.73. After 3 cycles of freezing-thawing permeability of clay isn’t being significant changed. The hydraulic conductivity of sand after freeze-thaw cycle is increased in 1.4-1.5 times before it was frozen.

Changing of water permeability of clay is explained by generation of layered cryogenic texture caused by frost heaving, water flux through macro- and micropores and slowly process of collapsing of pores under weight of soil. A high hydraulic conductivity and low threshold gradient after collapsing pores may be explained by residual porosity.

Increase of water permeability of soils after its freezing-thawing should be taken into account for designing of pavement structures, dams on frost-susceptible soils, landfill caps including clay barrier liners.

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