The newly laboratory equipment for exploring of freezing and thawing soils

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Abstract. Frost heaving is a challenge for geotechnical engineers in cold climate. Frost heave depends on two factors: the freezing rate and the velocity of water migration from unfrozen to frozen soil. The article deals with the existing apparatus for exploring frost heave which are systematized according to their purpose (measured parameters), design features and experimental conditions. The authors proposed the ways for improving laboratory equipment and presented newly developed apparatus for studying both the frost heaving and its consequences. The article presents apparatuses that allow controlling the freezing rate of soils by step-by-step movement of the freezing cell along the sample and providing even movement of the frost front in center and edges of the soil sample. Control of water migration to the frost front is carried out by making a vacuum in a base plate or using a porous item with a given water permeability. To study the impact of cyclic freezing-thawing on water permeability both along and across the cryogenic texture the authors developed a special apparatus in which horizontal permeability test is performed through the perforated double walls of multi-ring cell, vertical test- through bottom and top porous discs.

1. Introduction
Frost heaving is a challenge for geotechnical engineers in cold climate. Numerous studies showed that the primary frost heave caused by freezing of water contained in the soil is small. The main reason for the frost heave is the formation of ice lenses during freezing of water which are migrating to the frost front from the unfrozen soil. Now more than a dozen theories have been proposed to explain the mechanism of water migration, including capillary, osmotic, hydrodynamic and adsorption force theory. The latter, which is accepted by many researchers, is based on the concept of the adsorption-film migration mechanism. According to this theory at a negative temperature a layer of unfrozen bound water remains on the surface of the particles. Freezing soil seeks to maintain thermodynamic equilibrium by water absorption from the unfrozen soil. That is, the driving force of water migration is difference of the suction potential of unfrozen and freezing soil. This mechanism should be taken into account when designing laboratory equipment for studying the frost heave phenomenon.

2. Review of freezing test equipment
Many apparatus were developed for the frost heave studying of [1-16]. They can be systematized according to their purpose (measured parameters), design features, and experimental conditions. Principal schematic of apparatus for frost heave test are shown in Fig. 1.
The devices have the following design features:
- frost heave test is carried out on cylindrical soil samples with a diameter of 5 to 15 cm, the ratio of their height to diameter usually varies from 0.5 to 3;
- freezing of soil samples is performed, as a rule, from top to down;
- the samples are placed in a cylinder covered with a layer of thermal insulation, which provides steady-state one-dimensional heat flow along the sample;
- the overburden pressure on the samples is applied using a piston, its displacements are measured when freezing;
- free water supply is provided.

It should be noted that large laboratory apparatus are also known for testing specimens with dimensions 40×40 cm and 45 cm height [17], 70×80 cm and 40 cm in height [18].

In order to minimize side friction between surface of the frozen sample and inner surface of cylinder, the latter is made from separate rings with a movable joint. Lubricants and membranes are also used. In apparatus proposed by K.Kujala [10, 11] the bottom plate is possible to move along the cylinder (Fig.1b).

![Figure 1](image)

**Figure 1.** Principal schematic of apparatus for frost heave test in subject to direction of frost penetration: (a) – top-down; (b) – down-top; (c) - horizontal.

In most laboratory apparatus, as well as in-situ, the soil sample is frozen from top to down, and free water supply is provided from bottom. But T.Ishizaki, J.Kondrad, S.Freden studied frost heave phenomenon on apparatuses [9, 19-21], in which soil sample is frozen from down to top. Due to the frost heave deformations that are directed to unfrozen part of soil sample the influence of side friction was minimized.

Apparatus with horizontal movement of the frost front were used for assessment of frost heave around the columns during artificial ground freezing. Such devices can also be used for evaluation of frost heave on retaining walls and wells. Design of such apparatus can be one of the ways of development of the laboratory equipment.

Frost heave is mainly occurred due to the water migration from unfrozen to frozen soil, therefore, the slower the soil freezes, the greater frost heave phenomenon is appeared. That is why in laboratory
experiments the freezing rate in frost action is to be as close as possible to field conditions. It is impossible to fulfill this requirement at constant temperatures at the top and bottom ends of the soil sample. However, in advanced apparatus thermocouples are placed into the soil sample. Due to collecting and processing data the temperature at the "cold" end plate is controlled by a PC.

The water intake flux from unfrozen to frozen soil is usually determined by the flow rate of water from the supply tanks, less often - using water suction sensors placed into the sample. There were also attempts to use fluorescent substances to color the water migrating to frost front. Layer-by-layer sampling for water content after completed of the experiment is mandatory.

Taking into account the mechanism of the frost heave, the advantages and disadvantages of the existing laboratory equipment, authors formulate the main requirements for the design of apparatus for studying frost heave phenomenon:
- ability to control the freezing rate and the intensity of water migration flux;
- minimization of influence of side friction on the frost heave and cryogenic texture;
- minimization of manipulations with the soil sample before water permeability testing and defining the mechanical properties of soil after freezing-thawing.

According to the above mentioned requirements the authors designed new apparatus for studying frost heave phenomenon.

3. Enhancement of laboratory apparatus

An apparatus was created in 2012 that used a very simple way to provide a given freezing rate of the sample (Fig. 2) [22]. Moreover, the device allows to stop the frost front to observe the growth of ice lenses. It includes a cylinder mounted from several HDPE rings, freezing and cooling chambers, a processor designed to control the temperature in the chambers, register the temperature inside the sample and frost heave. The cylinder with the sample is placed in the cooling chamber, where the temperature is maintained at 0 ... + 2°C. Free water supply is carried out through the bottom end of the sample. The freezing chamber, in which a negative temperature is maintained using Peltier elements, moves along the sample from top to down. The freezing rate is determined by the velocity of movement of this chamber. LoadTrac-II frame by Geocomp (USA) is used to apply an overburden pressure on the sample. LoadTrac-II frame also provides measurement of frost heave with an accuracy of 0.001 mm.

Figure 2. Experimental apparatus for frost heaving test with controlled frost front penetration: (a) – photo of apparatus; (b) – schematic of apparatus.
The authors improved an original apparatus in which to ensure even movement of the frost front in center and edges of the soil sample dry mixture of special selected composition instead of thermal insulation are used (Fig. 3a). The thermal properties of the composition are priory defined by numerically simulation of laboratory apparatus when freezing of the soil sample in a special software (Fig. 3b) [23].

Figure 3. Experimental apparatus for frost heaving test: (a) - schematic of apparatus; (b) – numerical simulation.

The next step for improving apparatus is associated with the water migration control to the frost front. The presence of such a possibility, firstly, allows a deeper study of the frost heave phenomenon, and, secondly, take into account the groundwater level in soil stratum under building. In should be noted that standard apparatus provide only a free water supply to the bottom end of the soil sample with a height of about 15 cm, that is, the most unfavorable freezing conditions at the soil stratum are simulated.

The cylinders in the apparatus (Fig. 4a) filled with the soil are telescopic, that is, they are inserted into each other. It makes possible to mount a sample for laboratory testing with different heights and, in addition, to measure deformation below the frost front [24].

In the next apparatus, the aim is achieved by making a vacuum in a base plate (Fig. 4b) [25]. Freezing of the soil at a given groundwater level from the frost front is simulated by maintaining the negative pressure (below atmospheric pressure).

In the third apparatus (Fig. 3a), water migration is controlled by using special item placed under the bottom end of the soil sample with water permeability lower than the soil.
Figure 4. Laboratory apparatus for frost heaving test with controlled water flow.

Figure 5. Laboratory apparatus for frost heaving test with controlled water flow.

To study the effect of cyclic freezing-thawing on the water permeability of soils, the authors created an apparatus that allows to determine the frost heave deformations and water permeability of soils both along and across the ice lenses (Fig. 6) [26]. A special feature of the apparatus is a cell mounted from double-walled rings. The space between the walls in each of the rings are divided into four sectors. Two sectors with perforated inner walls are used for water drainage when water permeability test is carried out in the horizontal direction, and the other two - with non-perforated walls - for placing tubes for water drainage. After a given number of freezing-thawing cycles, water permeability tests are carried out without removing the sample from the cell. It allows to keep post-cryogenic texture of soil. The water flow is directed either horizontally through the perforated inner walls, or vertically through porous disks at the ends of the sample.
Figure 6. Laboratory apparatus for water permeability and frost heaving testing.

Thus, the newly laboratory equipment makes it possible to simulate the field conditions of soil freezing in the laboratory, to study the frost heave with given boundary conditions when testing and also to study the impact of cyclic freezing-thawing on the soil properties. The further enhancement of laboratory apparatus will improve the accuracy and reliability of assessment of frost-susceptibility of soils.

4. Summary
To obtain reliable results in the study of the frost heave phenomenon of soils laboratory equipment should provide the ability to control the freezing rate and the intensity of water migration flux, to minimize influence of side friction on the frost heave and cryogenic texture and exclude mechanical impact on the soil sample before water permeability testing and defining the mechanical properties of soil after freezing-thawing.

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