Коршунов, А.А. Индекс миграции влаги как характеристика пучинистости грунтов / А.А. Коршунов, С.В. Чуркин, А.Л. Невзоров // Construction and Geotechnics. – 2024. – Т. 15, № 3. – С. 79–90. DOI: 10.15593/2224-9826/2024.3.07

Korshunov A.A., Churkin S.V., Nevzorov A.L. Moisture migration index as a characteristic of soil heaving. *Construction and Geotechnics.* 2024. Vol. 15. No. 3. Pp. 79-90. DOI: 10.15593/2224-9826/2024.3.07

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CONSTRUCTION AND GEOTECHNICS
Т. 15, № 3, 2024
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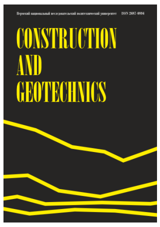

DOI: 10.15593/2224-9826/2024.3.07
УДК 624.131.436, 551.34

MOISTURE MIGRATION INDEX AS A CHARACTERISTIC OF SOIL HEAVING

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ARTICLE INFO

Received: 25 May 2024
Approved: 10 July 2024
Accepted for publication:
27 September 2024

Keywords:
frost heaving, moisture migration, freezing front, freezing rate, classification of heaving soils, closed system.

ABSTRACT

Frost heaving of clay soils can contribute to the development of significant deformations and mobilization of tangential forces during freezing of soils in the seasonally thawed layer of permafrost soils or on seasonally freezing soils. The existing characteristics for assessing soil frost heaving differ significantly in the methods of their determination according to international and Russian standards. The process of frost heaving is conditioned by the volume of moisture supplied to the freezing front and the rate of soil freezing. The purpose of the study is to identify the classification index determined by the intensity of moisture migration to the freezing front, under closed system conditions.

The studied clay soil samples had water content of 21.3 % and 22.8 %, dry density of 1.80 g/cm3 and 1.68 g/cm3, porosity factor of 0.50 and 0.60, respectively. Soil tests were carried out in a freezer on an installation designed by the authors and including 3 cells covered with a layer of thermal insulation and equipped with electronic temperature and displacement sensors which provide automatic recording of readings. The experiments were carried out according to three schemes, in two of which waterproof membranes were placed in the samples at different depths. Based on the results of the experiments it was obtained characteristic curves of deformations of heaving and freezing, as well as moisture redistribution in the samples. According to the value of moisture redistribution, the reduced moisture migration index which varies from 0.006 to 0.088 day-1was calculated. The power dependence of the reduced migration index on the freezing rate was obtained. This dependence can be used for numerical modelling of the stress-strain state of freezing freezing soil.

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ИНДЕКС МИГРАЦИИ ВЛАГИ КАК ХАРАКТЕРИСТИКА ПУЧИНИСТОСТИ ГРУНТОВ

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О СТАТЬЕ

Получена: 25 мая 2024
Одобрена: 10 июля 2024
Принята к публикации:
27 сентября 2024

Ключевые слова:
морозное пучение, миграция влаги, фронт промерзания, скорость промерзания, классификация пучинистых грунтов, закрытая система.

АННОТАЦИЯ

Морозное пучение глинистых грунтов может способствовать развитию значительных деформаций и мобилизации касательных сил при промерзании грунтов в сезонно-талом слое многолетнемерзлых грунтов или на сезонно промерзающих грунтах. Существующие характеристики для оценки пучинистости грунтов значительно отличаются по методам их определения по международным и российским стандартам. Процесс морозного пучения обусловлен объемом влаги, поступившей к фронту промерзания, и скоростью промерзания грунта. Целью исследования является установление классификационного показателя, определяемого по интенсивности миграции влаги к фронту промерзания, в условиях закрытой системы.

Исследованные образцы глинистых грунтов имели влажность 21,3 и 22,8 %, плотность скелета 1,80 и 1,68 г/см^3, коэффициент пористости 0,50 и 0,60 соответственно. Испытания грунтов выполняли в морозильной камере на установке, сконструированной авторами и включающей три ячейки, покрытые слоем теплоизоляции и оснащенные электронными датчиками температуры и перемещений, обеспечивающими запись показаний в автоматическом режиме. Эксперименты проводили по трем схемам, в двух из которых в образцах были размещены водонепроницаемые мембраны на различной глубине. По результатам экспериментов получены характерные кривые деформаций пучения и промерзания, а также перераспределение влаги в образцах. По величине перераспределения влаги рассчитан приведенный индекс миграции влаги, который варьируется от 0,006 до 0,088 сут$^{-1}$. Получена степенная зависимость приведенного индекса миграции от скорости промерзания, которая может быть использована для численного моделирования напряженно-деформированного состояния промерзающих пучинистых грунтов.

Introduction

According to the results of research published in the UN report on the problems of sustainable development the global average annual temperature on the planet has increased by 1.1 °C over the past 70 years [1]. This trend poses the greatest danger to the areas of permafrost distribution where from 30 to 50 % of infrastructure facilities fall into the zone of active influence of climate change [2–5]. The consequence of temperature increase is not only the precipitation of buildings and structures caused by the degradation of permafrost, but also the outgrowth of frost heave deformation of soils associated with the larger depth of seasonal freezing-thawing. Frost heave can lead to the uplift of oil and gas pipeline supports, pile foundations of low-rise buildings, deformation of highways and hydraulic structures. That is why the improvement of the accuracy of soil frost heave assessment is becoming the most important task.

To date, many devices have been developed to study frost heaving of soils [6–8]. As a rule, cylindrical specimens with a diameter of 5 to 15 cm are tested; the ratio of their height to diameter usually varies from 0.5 to 3. The specimens are placed in a cylinder tube covered with a layer of thermal insulation, which provides a predominantly upward-directed heat flow, and they are freely fed with water from below.

It should be noted that, in addition to the variety of applied devices and methods, in the international and Russian practice different indicators of soils classification according to the degree of heaving are used. In particular, in the regulatory documents of Russia and Great Britain it is used relative deformation of heaving, in the USA – heaving rate [6, 9–11]. The indicator called segregation potential has become widespread; it is calculated as the ratio of the moisture migration rate in the sample to the temperature gradient within the frost penetration rim [9, 12–16]. It should be noted that its calculation causes certain difficulties in determining the thickness of the freezing rim, since it is impossible to perform its direct measurements during the experiment.

The forecast ofingfrost heave deformations should be based on the analysis of this very complex and multifactorial natural process. It is known that during freezing three zones are conventionally formed in the soil – frozen, freezing (transitional) and thawed. Owing to low water permeability of frozen soil and insignificant amount of unfrozen moisture the first zone is characterized by almost complete absence of moisture transfer. In the freezing zone, intensive phase transitions take place, and changes in the moisture potential lead to its migration from the thawed zone. The degree of compensation of the changing potential is determined by the ability of the soil of the thawed zone to give up a certain amount of pore moisture. Moisture migrating from the upper part of the thawed zone forms ice lenses, causing ground heaving. In addition to the intensity of moisture migration, the size of lenses and their growth rate are also determined by the rate of freezing front movement. At high freezing rate moisture does not have time to migrate to the freezing front, and it is observed predominantly freezing of moisture contained in pores Small temperature gradients, on the contrary, provide an opportunity for more moisture to enter the freezing zone and the development of frost heave deformations. Thus, the results of the tests on the soil heaving according to the existing methods are determined not only by the properties of the soil itself, but also by external factors – temperature gradient and conditions of the sample feeding (under constant load).

The application of the reduced migration index as a classification index, which the authors propose to determine according to a closed scheme, without feeding the sample with water, will make possible to reduce the influence of the above mentioned factors in the assessment of the soil heaving.

Methods of the experiment

The study of moisture migration during freezing was carried out on samples of clayey soils taken in the Arkhangelsk Region; their properties are presented in the Table. Tests were carried out on specimens with a diameter of 100 mm and a height of 150 mm.

Physical properties of soils

Физические характеристики грунтов

Serial number	Names of Physical properties	Clay (EGE-1)	Loam soil (EGE-2)
1	Water content, W, %	21,3	22,8
2	Plastic limit, PL, %	18,5	15,0
3	Liquid limit, LL, %	45,0	31,7
4	Plasticity index, PI, %	26,5	16,7
5	Bulk density, ρ, g/cm^3	2,18	2,06
6	Specific gravity, ρ_s, g/cm^3	2,71	2,67
7	Dry density, ρ_d, g/cm^3	1,80	1,68
9	Porosity factor, e	0,50	0,60

The unit for studying frost heaving, presented in Fig. 1, allows testing three samples simaltaneously. The sample cell is made of rigid polyurethane foam with a wall thickness of 40 mm. The lower end of the cell shall be covered with a waterproof film in a closed circuit test or shall remain open in a water-fed test. The cell with soil is installed on a sandy base equipped with a heating cable. The temperature at the lower end of the sample is maintained at +2…+4 °C. Temperature sensors are placed inside the sample with 50 mm spacing, as well as under the die. To control soil moisture, an electrical resistance measurement system is used. Electrodes for resistance measurement are placed along the height of the specimen also in 50 mm increments. During the tests the unit is located in a freezing chamber in which the temperature +1…+2 °C is maintained during pre-cooling of samples and minus 3…6 °C – during their freezing. Along the lateral surface, the cell with the soil was covered with additional polyethylene pipe insulation to exclude heat losses through the places of installation of temperature and resistance sensors.

a *b*

Fig. 1. Installation for heaving study: *a* – general view; *b* – test cell
Рис. 1. Установка для исследования пучения: *a* – общий вид;
b – ячейка для испытаний

The unit allows automatic recording of displacement and temperature sensor readings. Displacement sensors provide measurements with an accuracy of ± 0,001 mm, temperature sensors – ± 0,1°C.

The studies were carried out according to the closed scheme, excluding the influence of the conditions of the samples feeding on frost heaving. Under conditions of steady heat flow, when the temperature gradient is constant, the migration intensity should be considered as a characteristic of soil heaving, which is conditioned solely by the nature of the soil itself, in particular, its mineralogical composition and physical properties.

The samples were kept in the chamber until they reached a temperature of +1…+2 °C, after that the freezing of samples was started. The temperature in the freezing chamber was regulated in such a way as to ensure a freezing rate of 5–20 mm/day at the initial stage.

Further experiments were performed according to three schemes. In the first of them, the freezing front in clay samples (EGE-1) was stopped at a given depth and the frost heave deformations were observed. In the second scheme, a waterproof membrane was placed in the loam samples (EGE-2) at a depth of 50 mm from the top face. In the third test scheme waterproof membranes were installed in loam samples (EGE-2) at a depth of 50 and 100 mm from the upper end. After stabilizing the position of the freezing front (according to the first scheme) or reaching the freezing depth of 90… 100 mm (according to the second and third schemes) the experiment was completed and the samples were removed from the device to control the distribution of moisture in the sample. On the extracted samples, the cryogenic texture was carefully studied and the moisture was determined from the height of the samples at 15… 20 mm intervals.

Results

In experiments on freezing samples according to a closed scheme a monotonic increase in heaving deformations is observed under conditions when the freezing front is practically stopped (the freezing rate did not exceed 0.3… 0.5 mm/day) (Fig. 2). This is explained by the formation of lenses due to migration to the freezing front. The study of the samples after the experiment showed the presence of ice schliers in them with a thickness of 0.5… 2.0 mm (Fig. 3). The moisture profile of one of the samples is shown in Fig. 4.

The monotony of the increment of heaving deformations is caused exclusively by the redistribution of pore moisture due to changes in the moisture potential during freezing and the appearance of absorption forces. The intensity of the migration flow under the conditions of a freeze front stop characterizes the ability of the soil to transport pore moisture to the freezing zone.

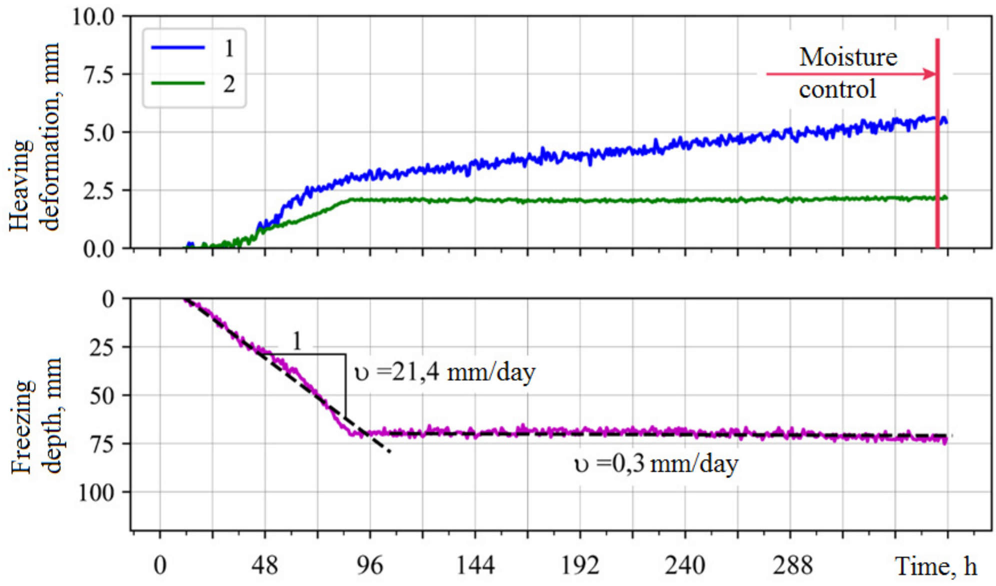

Fig. 2. Heaving and freezing curves of the sample (EGE-1): *1* – general heaving deformations; *2* – heaving deformations caused by freezing of initial pore moisture

Рис. 2. Кривые пучения и промерзания образца (ИГЭ-1): *1* – общие деформации пучения; *2* – деформации пучения, обусловленные замерзанием начальной поровой влаги

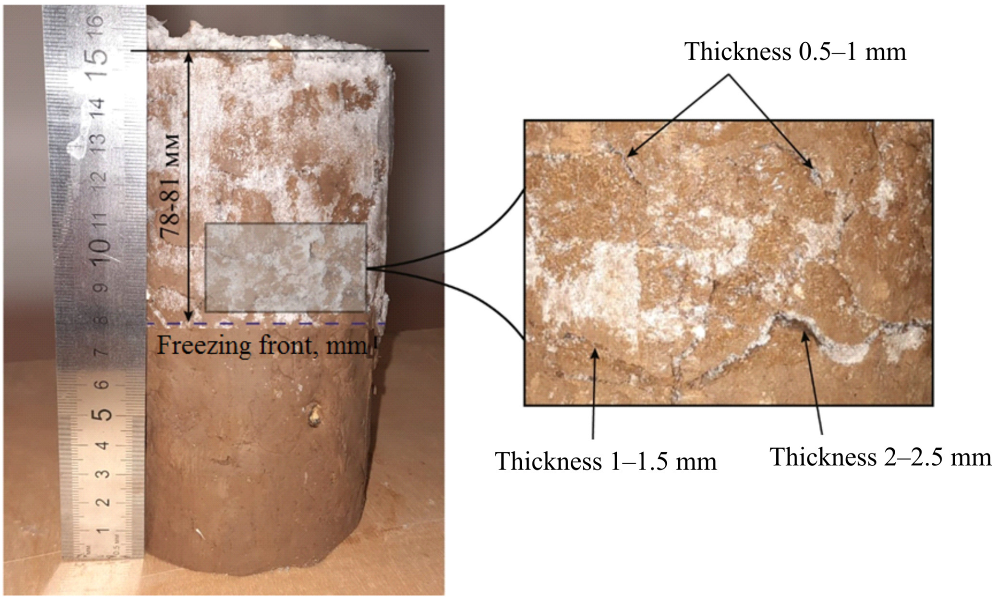

Fig. 3. A sample of clayey soil after freezing according to scheme 1
Рис. 3. Образец глинистого грунта после промерзания по схеме 1

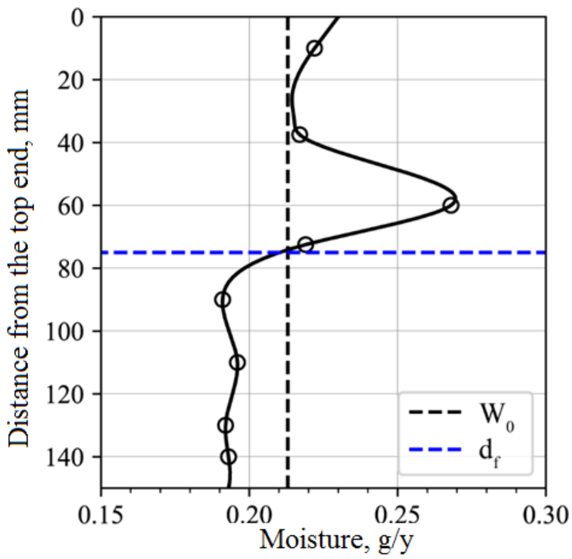

Fig. 4. Moisture profile. Test Scheme 1
Рис. 4. Профиль влажности. Схема испытаний 1

The results of freezing of samples with waterproof membranes placed at a depth of 50 mm showed that at freezing rate equal to 4–6 mm/day the change in sample moisture content due to migration is $(79{,}8\ldots84{,}2)\cdot10^{-3}$ g/y (Fig. 5). At the rate of 16…19 mm/day the amount of migrated moisture amounted to $(4{,}8\ldots5{,}0)\cdot10^{-3}$ g/y, which stipulated by low water permeability of clayey soils and high rate of movement of the freezing front. The characteristic moisture profile of the samples during testing according to scheme 2 is presented in Fig. 6.

Heaving of the upper part of the samples (above the waterproof membrane) develops more intensively in the initial period of time, which is characterized by a rapid pulling of moisture to the freezing front. Further, the heaving rate slows down sharply, which is due to the depletion of the pore moisture reserve above the membrane. The remaining pore moisture freezes in the sample.

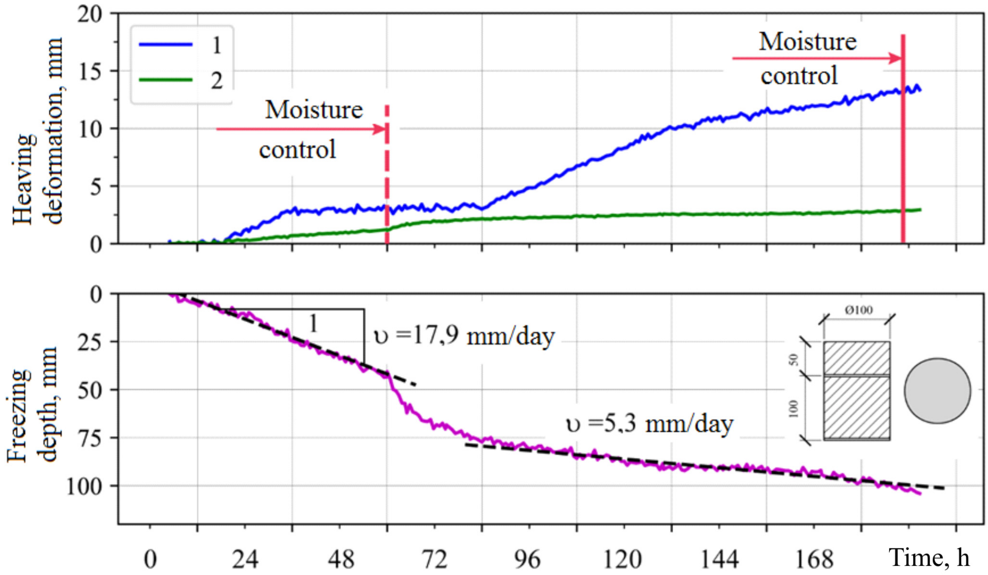

Fig. 5. Frost heave and freezing curves of the sample (EHE-2): *1* – general frost heave deformations; *2* – frost heave deformations caused by freezing of initial pore moisture
Рис. 5. Кривые пучения и промерзания образца (ИГЭ-2): *1* – общие деформации пучения; *2* – деформации пучения, обусловленные замерзанием начальной поровой влаги

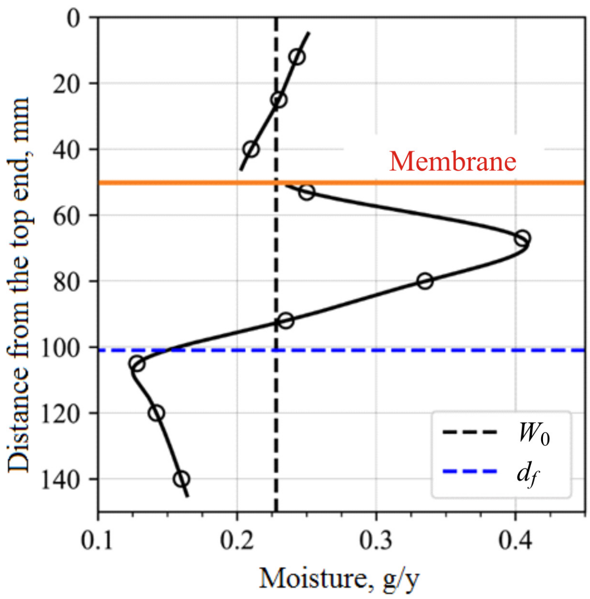

Fig. 6. Moisture profile. Test scheme 2
Рис. 6. Профиль влажности. Схема испытаний 2

Heaving of the lower part of the sample (under the membrane) is practically not manifested in the initial period of time, which is explained by the high rate of freezing. Further, when the freezing rate is reached equal to 5 mm/day, freezing occurs under conditions of a stationary heat flow and is accompanied by the growth of heaving deformations at a constant rate.

A similar situation is observed during freezing of samples with waterproof membranes placed at a depth of 50 and 100 mm (Fig. 7). When the freezing front approaches the 2nd waterproof membrane (the section corresponding to 120–168 h), the rate of heaving slows down. This is also associated with the depletion of pore moisture in the soil between the two membranes.

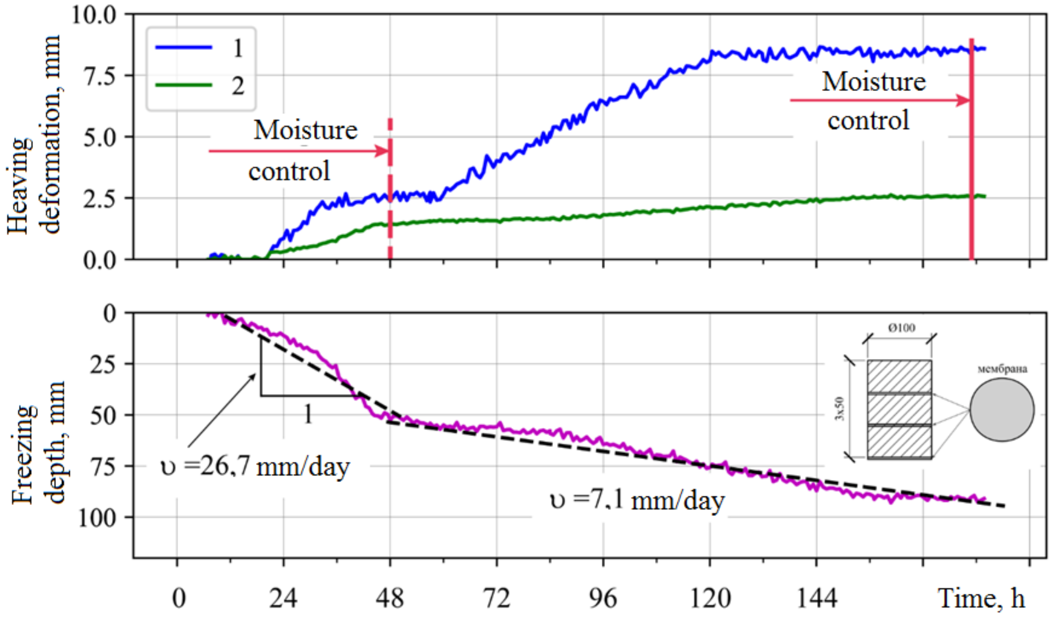

Fig. 7. Frost heave and freezing curves of the sample (EHE-2): *1* – general frost heave deformations; *2* – frost heave deformations caused by freezing of initial pore moisture

Рис. 7. Кривые пучения и промерзания образца (ИГЭ-2): *1* – общие деформации пучения; *2* – деформации пучения, обусловленные замерзанием начальной поровой влаги

The results of experiments show that at freezing rate equal to 6–8 mm/day the moisture content change due to migration is $(14,1\ldots16,1)\cdot10^{-3}$ g/y, at 25–27 mm/day – $(3,0\ldots3,6)\cdot10^{-3}$ g/y. The characteristic moisture profile of samples under testing according to scheme 3 is presented in Fig. 8.

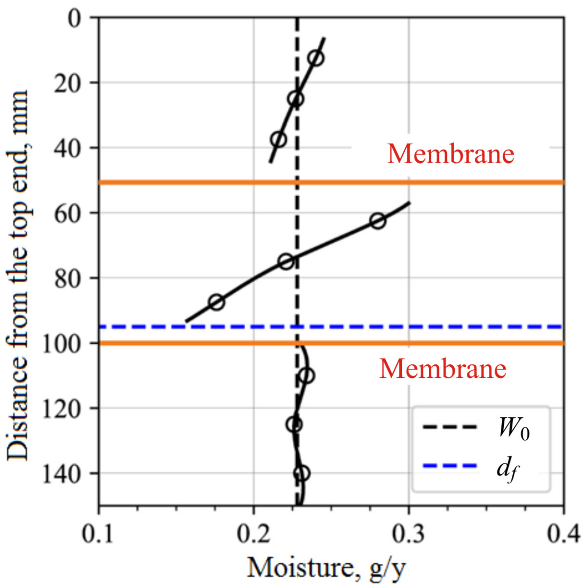

Fig. 8. Moisture profile. Test scheme 3

Рис. 8. Профиль влажности. Схема испытаний 3

The value of heaving can be found by the known dependencies [17, 18]:

$$h_f = h_f^{\mathrm{I}} + h_f^{\mathrm{II}} = \left[0,09\left(\theta_0 - \theta_w\right) + 1,09\left(\theta - \theta_0\right)\right] \cdot d_f \quad (1)$$

where h_f^{I}, h_f^{II} – heaving deformations due to freezing of water originally contained in the soil, and due to moisture migration, respectively; θ_0 – initial volume moisture of the soil, cm^3/cm^3; θ_w – volume moisture owing to unfrozen moisture content, cm^3/cm^3; θ – the final volume moisture of soil in the frozen zone, cm^3/cm^3; d_f – freezing depth, cm.

Calculation by formula (1) showed that at $\theta_0 = W_0 \cdot \rho_d = 0,213 \cdot 1,803 = 0,384$ cm^3/cm^3, $\theta_w = 0,027 \cdot 1,803 = 0,049$ cm^3/cm^3 and $\Delta\theta = 0,019 \cdot 1,803 = 0,034$ cm^3/cm^3 frost heave deformations are $h_f = 5,0$ mm, what is close to the experimental data (5.5 mm). When calculating the heaving deformations, the final soil moisture θ_0 was determined by the moisture profile obtained from the results of the experiments. Similar calculations were performed for the samples tested according to schemes 2 and 3, and the values of heaving close to the experimental data were obtained. The discrepancy amounted to 0.5–2 mm.

Discussion

Taking into account that all the tests were carried out under a closed scheme, the obtained redistribution of moisture in the samples is associated solely with the nature of the studied clayey soil. In the experiments with waterproof membranes, different freezing conditions were actually modeled and for each of them the values of migration intensity were obtained, which allows for each sample in the areas isolated by membranes to obtain the parameters of moisture migration flow and to estimate the soil heaving. In experiments with freezing front stopping the values of moisture migration intensity characterizing the maximum moisture inflow under given conditions, caused by full mobilization of absorbtion forces, were determined. Accordingly, such a characteristic can be applied to classify the soil looseness.

The value of the given migration index can be used as a classification indicator:

$$I_w = \frac{\Delta\theta/\theta_0}{\Delta t} = \frac{\Delta W/W_0}{\Delta t} \quad (2)$$

where $\Delta\theta$, ΔW – change in the volume and weight moisture content of the soil, respectively.

The scheme for determining the change in moisture is presented in Fig. 9, where it is indicated: θ_0, W_0 – initial volumet and weight moisture content, respectively; Δt – time interval for determining moisture change.

Based on the test results, the power dependence of the reduced migration index on the freezing rate was obtained:

$$I_w = A \cdot \upsilon^B \quad (3)$$

where υ – freezing rate, mm/day; A, B – coefficients depending on the type of clayey soil. The curve of the migration index is presented in Fig. 10.

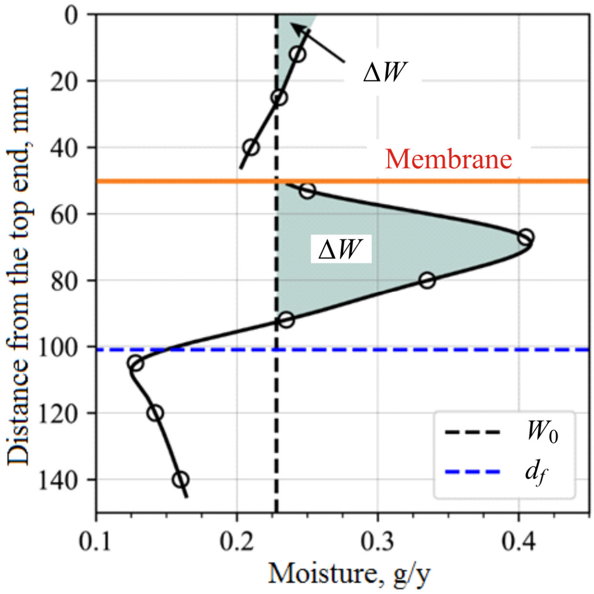

Fig. 9. On the Determination of Humidity Changes (on the example of profile No 2)
Рис. 9. К определению изменения влажности (на примере профиля № 2)

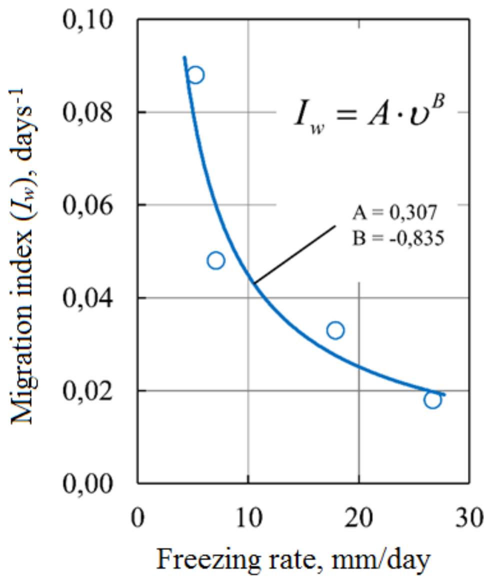

Fig. 10. Curve of the moisture migration index for the sample EGE-2
Рис. 10. Кривая индекса миграции влаги для образца ИГЭ-2

Conclusion

Based on the results of the studies of freezing clayey soils according to a closed scheme (in the absence of water recharge), the following conclusions can be drawn:

1. Heaving soils can be classified according to the given migration index, determined by the value of moisture redistribution in a closed system under conditions of prolonged freezing front stoppage.

2. Dependence of freezing index (I_w) of the freezing rate is determined by the power function $I_w = A \cdot \upsilon^B$, where A, B – are coefficients depending on the type of clay soil.

3. The given migration index, which is the relative rate of moisture redistribution in time, can be used to calculate heaving deformations and numerical simulation of the stress-strain state of freezing heaving soils.

Финансирование. *Работа выполнена при финансовой поддержке Российского научного фонда (грант № 22-19-20026).*

Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*

Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации.*

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