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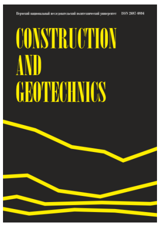

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ANALYSIS OF THE CURRENT STATE OF THE PROBLEM OF CIVIL ENGINEERING IN THE CONDITIONS OF PERMAFROST SOILS

A.B. Ponomaryov[1], **D.S. Korablev**[2]

[1]Saint Petersburg Mining University, Saint Petersburg, Russian Federation
[2]Saint Petersburg State University of Architecture and Civil Engineering, Saint Petersburg, Russian Federation

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ABSTRACT

The peculiarities of the Russian Federation geographical location predetermine the need to develop infrastructure in the territories composed of permafrost soils. At the same time, the construction of buildings and structures in the permafrost zone is associated with the presence of additional risk factors due to the development of deformation processes in the foundations under the condition of changes in their temperature regime. Thawing of permafrost soils is accompanied by the destruction of the natural structure of soil bases and leads to a sharp increase in deformations of buildings and structures erected in areas of permafrost soil distribution. The article is devoted to the determination of thawing deformations and represents an overview of existing methods for calculating the thawing settlement of permafrost soils. The basic principles of calculating thawing bases are considered and the factors influencing the complexity of predicting thawing deformations are revealed. On the basis of the existing mathematical dependencies, the main components of thawing deformations are identified. The existing analytical and numerical methods of calculation of thawing deformations have been analyzed, and the applicability of the existing calculation methods has been assessed. On the basis of existing studies the basic principles of stress-strain state changes of soil during thawing have been revealed. The physical and mechanical processes occurring in thawing foundations at the micro- and macro level have been considered. The influence of these processes on strength, deformation and filtration properties of soils during thawing has been analyzed. The main stages of development of thawing deformations in the soil mass have been identified. The prerequisites have been considered and the basic principles of solving the problems of foundations thawing by numerical methods have been described. The analysis of existing models of thawing of permafrost soils has been carried out. The basic principles of formation of computational models of freezing and thawing of soil foundations have been highlighted.

© **Andrey B. Ponomaryov** – Doctor of Technical Sciences, Professor, e-mail: andreypab@mail.ru.
Denis S. Korablev – Postgraduate Student, e-mail: d.korablv@yandex.ru.

Пономарев Андрей Будимирович – доктор технических наук, профессор, e-mail: andreypab@mail.ru.
Кораблев Денис Сергеевич – аспирант, e-mail: d.korablv@yandex.ru.

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АНАЛИЗ СОВРЕМЕННОГО СОСТОЯНИЯ ПРОБЛЕМЫ ПО СТРОИТЕЛЬСТВУ ЗДАНИЙ И СООРУЖЕНИЙ В УСЛОВИЯХ ЗАЛЕГАНИЯ ВЕЧНОМЕРЗЛЫХ ГРУНТОВ

А.Б. Пономарев[1], Д.С. Кораблев[2]

[1]Санкт-Петербургский горный университет, Санкт-Петербург, Российская Федерация
[2]Санкт-Петербургский государственный архитектурно-строительный университет, Санкт-Петербург, Российская Федерация

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АННОТАЦИЯ

Особенности географического положения Российской Федерации предопределяют необходимость развития инфраструктуры на территориях страны, сложенных вечномерзлыми грунтами. При этом строительство зданий и сооружений в криолитозоне сопряжено с наличием дополнительных факторов риска, обусловленных развитием деформационных процессов в основаниях при условии изменения их температурного режима. Оттаивание вечномерзлых грунтов сопровождается разрушением природной структуры грунтовых оснований и приводит к резкому росту деформаций зданий и сооружений, возводимых в районах распространения вечномерзлых грунтов. Статья посвящена определению деформаций оттаивания и представляет собой обзор существующих методов расчета осадки оттаивания вечномерзлых грунтов. Рассмотрены основные принципы расчета оттаивающих оснований и выявлены факторы, оказывающие влияние на сложность прогнозирования деформаций оттаивания. На основании существующих математических зависимостей, выделены основные составляющие деформаций оттаивания. Выполнен анализ существующих аналитических и численных методик расчета деформаций оттаивания, выполнена оценка применимости существующих методов расчета. На основании существующих исследований выявлены основные принципы изменения напряженно-деформированного состояния грунта при оттаивании. Рассмотрены физико-механические процессы, происходящие в оттаивающих основаниях на микро- и макроуровне. Выполнен анализ влияния этих процессов на прочностные, деформационные и фильтрационные свойства грунтов при оттаивании. Выделены основные этапы развития деформаций оттаивания в грунтовом массиве. Рассмотрены предпосылки и описаны основные принципы решения задач оттаивания оснований численными методами. Выполнен анализ существующих моделей оттаивания многолетнемерзлых грунтов. Выделены основные принципы формирования расчетных моделей промерзания и оттаивания грунтовых оснований.

Introduction

Almost a quarter of the Earth's land is located on the territories composed of permafrost soils. A peculiarity of the geographical location of the Russian Federation is the share of cryolithic zone: permafrost soils occupy up to two thirds of the total area of the country including the richest in natural wealth and resources areas which require the construction of the appropriate infrastructure for development and exploration (Fig. 1).

The unique features of permafrost soil construction properties are associated with the presence of additional risk factors, caused, first of all, by possible changes in the temperature regime of permafrost soil bases during construction or operation of erected structures [1, 2]. In addition, the reasons for the development of accidents at construction sites in the cryolithic zone can also be caused by climatic changes affecting the territory of the Russian Federation, which has been repeatedly recorded by the researchers [3–6].

The first studies of the processes of freezing and thawing of soils were carried out at the end of the nineteenth century in Russia owing to the construction of the Trans-Siberian Railway and summarized by N.S. Bogdanov [7]. Industrialization, the growth of industrial production and mining at the beginning of the twentieth century predetermined the need to develop territories located in the cryolithic zone and required the development of a new scientific direction – the mechanics of frozen soil.

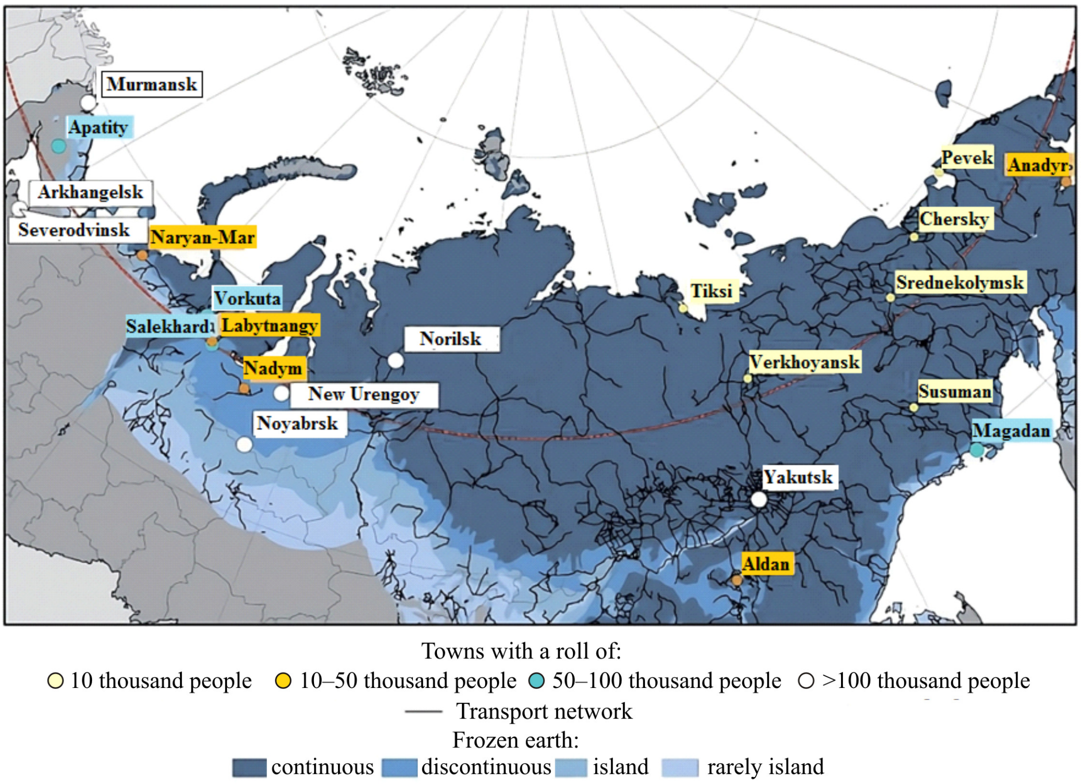


Fig. 1. The boundaries of the permafrost zone of Russia with the indication of the largest residential places (ROSHYDROMET, 2022)

Рис. 1. Границы криолитозоны России с указанием крупнейших населенных пунктов (РОСГИДРОМЕТ, 2022)

The first comprehensive theoretical, laboratory and field studies of the properties of soils in the process of their thawing and freezing were carried out by M.I. Sumgin and N.A. Tsytovich in the 30s of the twentieth century [8, 9]. The principle of equilibrium state of phase transitions of water in soil, proposed by N.A. Tsytovich, explained the phenomenon of moisture migration, which affects the formation and destruction of cryogenic textures and structures determining the physical properties of frozen soil, and formed the basis of the first mathematical models describing temperature and humidity transformations in soils [10, 11] (Fig. 2).

The greatest danger to the buildings and engineering structures arranged on permafrost soils is represented by deformation processes invariably accompanying temperature transformations in the soil mass. Freezing of thawed soils leads to the development of deformation of frost heaving due to the transition of moisture contained in the soil into ice and continuous migration of moisture to the freezing front [12, 13]. At the same time, thawing of soils which were originally frozen is accompanied by the destruction of the cryogenic texture of the soil, almost complete loss of structural strength, and leads to a sharp increase in the rate of foundation deformations development [14, 15]. The development of thawing deformations in time is complicated by a sharp increase of soil permeability compared to non-frozen soils of the same composition and consistency, which leads to the acceleration of the soil mass consolidation processes [16] (Fig. 3).

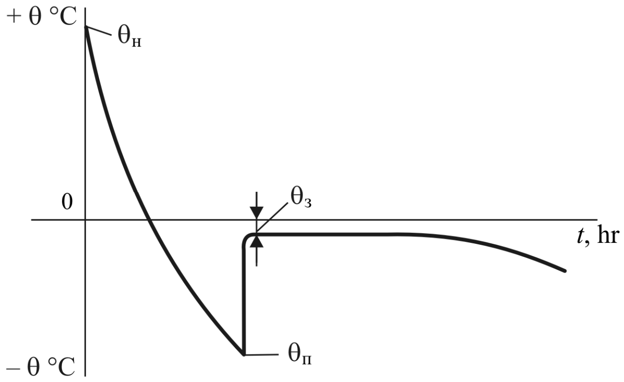


Fig. 2. The curve of cooling and freezing the soil: $\Theta_{з}$ – temperature of freezing the soil;
$\Theta_{п}$ – the temperature of the beginning of the pore liquid freezing (N.A. Tsytovich [12])
Рис. 2. Кривая охлаждения и замерзания грунта: $\Theta_{з}$ – температура замерзания грунта;
$\Theta_{п}$ – температура начала замерзания поровой жидкости (Н.А. Цытович [12])

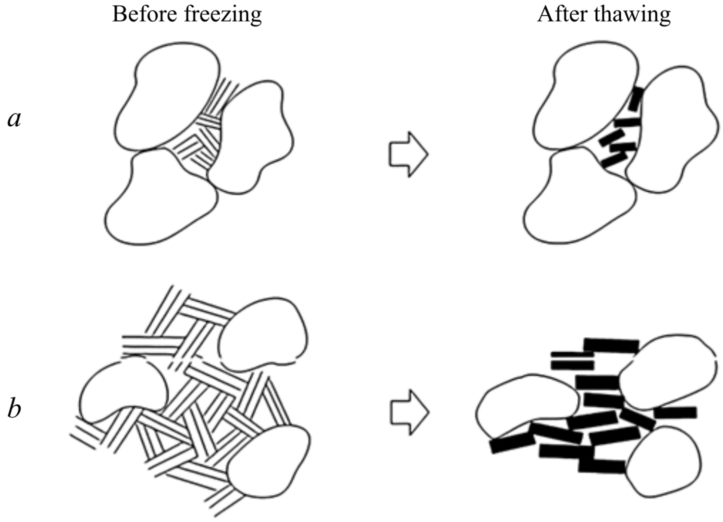


Fig. 3. Changes in the soil structure in the process of freezing-thawing:
a – dusty loam; *b* – loam (E.J. Chamberlain [16])
Рис. 3. Изменения структуры грунта в процессе замораживания-оттаивания:
а – пылеватой супеси; *b* – суглинка (E.J. Chamberlain [16])

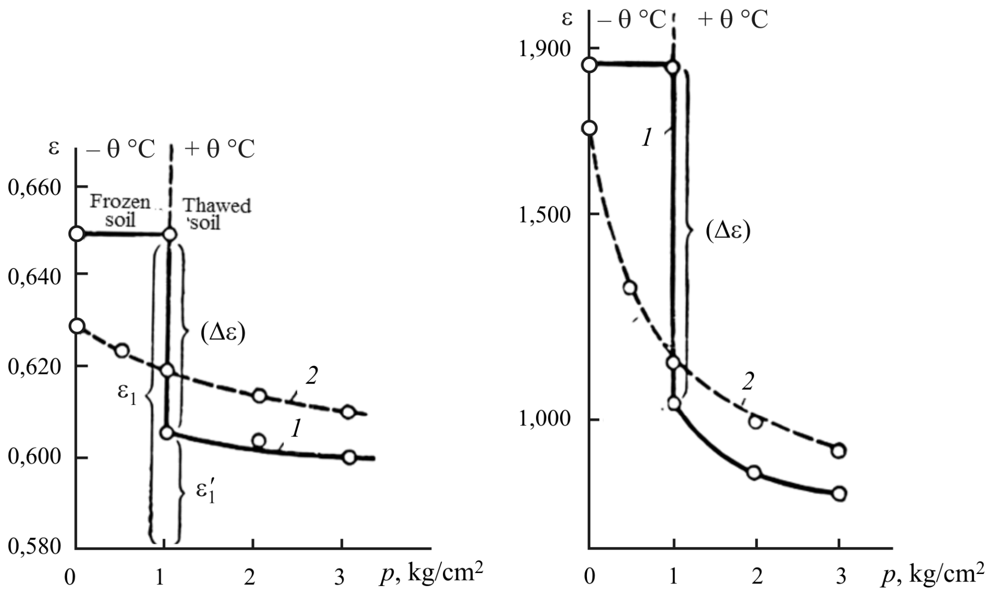
Prediction of thawing deformations is complicated by the complexity of physical and mechanical processes in the course of thawing and extremely high sensitivity to the properties of soils before temperature transformations. Features of the engineering, geological and geocryological structure of thawing soils, namely, the type of permafrost distribution, the genesis of foundations, the combination of physical, mechanical and thermo physical properties of thawing soils, as well as the climatic features of the construction area affect the magnitude and rate of deformations development during thawing [17–19].

Existing methods for determining permafrost soils thawing deformations

N.A.Tsytovich was the first who studied the compressibility of permafrost soils using an odometer with a heated metal stamp which provided one-sided thawing of the sample. Further, these studies were realized in the field with the application of hot stamps [20].

During the development of the analytical method for calculating the settlements it was proposed to divide the deformations of thawing soil into two components – the settlement obtained only from the gravity load of the soils during thawing and the settlement from external action. Such a division has remained practically unchanged to this day as a part of the current regulatory documents (SR 25.13330).

In accordance with the research of N.A. Tsytovich two opposite processes are observed during the frozen soils thawing: soil compaction due to the squeezing of the melted pore fluid and swelling of soil particles which increases the porosity of the thawed soil. At the same time there is a sharp increase in the compressibility of the soil after thawing (on average by an amount 3–4 times higher than the initial value). The proposed mechanical characteristic determining the value of thawing settlement is the thawing coefficient which characterizes the change in the porosity coefficient of frozen soils during thawing [21] (Fig. 4).



a *b*

Fig. 4. Compression curves for sand (*a*) and clay (*b*) during thawing (N.A. Tsytovich [21])
Рис. 4. Компрессионные кривые для песка (*a*) и глины (*b*) при оттаивании (Н.А. Цытович [21])

Subsequently, the methods for calculating thawing deformations were continuously improved. Further studies devoted to the problem of compression compressibility were made by G.I. Lapkin and M.N. Goldstein in the middle of the XX century [22]. The obtained theoretical dependences are based on the condition of pore moisture squeezing in the process of consolidation to the moisture content corresponding to the lower limit of soil plasticity. In addition, experimental studies have shown that soils containing large interlayers or lenses of ice are not fully consolidated during thawing.

A.M. Pchelintsev proposed to determine the settlement of thawing soils by quantifying the destruction of the cryogenic texture on the basis of the difference between the total moisture content of the permafrost soil and the moisture content of the mineral part of the cryogenic texture [23]. At the same time, this dependence did not take into account soil deformations due to compaction under external pressure and was applicable only to soils whose pore space is completely filled with ice.

The calculation method of thawing settlement proposed by Pchelintsev was developed in the works of F.G. Bakulin and V.F. Zhukov [24–26]. The obtained dependences take into account the cryogenic structure and composition of soils and are based on the determination of the change in the volume fraction of ice, water and air components contained in the pores of frozen soil during thawing.

A different mechanism for calculating thawing settlement based on dependencies on physical characteristics was proposed by M.F. Kiselev [27]. Calculation of thawing deformations in accordance with M.F. Kiselev's model is based on the calculation of the thawed soil volume change. The influence of the soil structure and the dependence of compaction on the external pressure were supposed to be taken into account using the empirical compaction coefficient.

Attempts have been made to describe thawing deformations on the basis of empirical dependencies of changes in the weight moisture content of soils during thawing. I.N. Votyakov proposed a calculation formula assuming the dependence of soil moisture in relation to the reduced height of ice in the soil [28].

A.N. Davydochkin proposed a calculated dependence for determining the settlement of thawing soil considering the presence of layers and lenses of ice in the soil [29]. At the same time the formula has a number of limitations in terms of applicability since it does not take into account the cryogenic structure of the samples which is different from the layered one.

Foreign studies also contributed to the development of calculation methods for determining the deformations of permafrost soils. The method for calculating thawing settlement proposed by F. Crory uses the dependencies of changes in deformations on humidity, ice content and the porosity coefficient in the frozen and thawed state [30].

Investigation of clayey soils during the construction of the pipeline in the Mackenzie River Valley allowed G.H. Watson, R.K. Rowley, W.A. Slusarchuk, L.D. Keil, N.M. Nillsen, R.C. Gupta to identify empirical dependencies of thawing deformations on changes in the volume of thawed soil which were further refined by other researchers [31–33].

Each of the formulas obtained by researchers for determining the settlement of thawing soils has a number of assumptions and limitations of applicability: some calculated dependencies are applicable only to clayey soils, some use erroneous ideas about the physical and mechanical processes occurring in thawing soils, and some use empirical dependencies that are valid only for soils of a certain structure and genesis. The main analytical solutions obtained for the determination of thawing settlement are presented in the Table.

Calculation formulas for determining thawing settlement

Расчетные формулы для определения осадки оттаивания

Authors	Calculation formulas	Number
Tsytovich N.A.	$S = A_{th} + \sum_{i=1}^{n} m_{ith} p_i$	(1)
Goldstein M.N.	$S = \frac{1.09\left(W - W_p\right)\rho}{\left(1 - W\right)\rho_w} \cdot h$	(2)
Pchelintsev A.M.	$S = \frac{\rho_s \cdot \rho_w \cdot k_2\left(W - W_m\right)h}{\left(1 + 0.09i\right)W - W_m + \frac{\rho_w}{\rho_{df}}}$	(3)

The end of the Table

Authors	Calculation formulas	Number
Bakulin F.G., Zhukov V.F.	$S = \dfrac{(1+0.09i)W - W_m}{(1+0.09i)W - W_m + \dfrac{\rho_w}{\rho_{df}}}$	(4)
Kiselev M.F.	$S = \left[1 - \rho_{df}\left(\dfrac{1}{\rho_s} + \dfrac{1}{\rho_w}\left(W_p + k_3 I_p\right)\right)\right] \cdot h$	(5)
Votyakov I.N.	$S = \dfrac{k_5 W}{2.7W + 0.9}$	(6)
Davydochkin A.N.	$S = \dfrac{\rho_s \cdot (W - \rho_i W_m) h}{(1+0.09i)W - W_m + \dfrac{\rho_w}{\rho_{df}}}$	(7)
Vyalov S.S	$S = S_{i0} + {\dfrac{\tau_i}{\eta_0\left[1 - n(\tau_i,\, \sigma_m)\right]^{t}}}^{1-n(\tau_i,\, \sigma_m)}$	(8)
Crory F.	$S = \dfrac{W_f(1+0.09i) - W_{th}}{\dfrac{(1{,}09W_f - 0.09iW_{af})}{e_f} + W_f(1+0.09i)}$	(9)
Watson G. H., Rowley R. K., Slusarchuk W. A.	$S = \left[0.8 - 0.868\left(\dfrac{1}{\rho_w} - 1.15\right)^{\frac{1}{2}} \pm 0.05\right] \cdot h$	(10)
Keil L.D., Nillsen N.M., Gupta R.C.	$S = \left[0.9 - 0.691\left(\dfrac{1}{\rho_w} - 0.236\right)^{\frac{1}{2}} \pm 0.05\right] \cdot h$	(11)
Amiri S.A.G	$S = S_{me} + S_{se} + S_{mp} + S_{sp}$	(12)
Xin Li, Enlong L., Bingtang S., Xingyan L.	$S = \begin{cases} \dfrac{\sigma_1 - \sigma_3}{3G_0} + \dfrac{\sigma_1 - \sigma_3}{3G_1}\left[1 - \exp\left(-\dfrac{2G_1}{\eta_1}t\right)\right], & F < 0 \\ \dfrac{\sigma_1 - \sigma_3}{3G_0} + \dfrac{\sigma_1 - \sigma_3}{3G_1}\left[1 - \exp\left(-\dfrac{2G_1}{\eta_1}t\right)\right] + \dfrac{1}{\eta_2(H,D)}FMt, & F \geq 0 \end{cases}$	(13)

Note. Conventional signs in formulas (1)–(13): ρ – density of frozen soil, g/cm^3; ρ_i – ice density, g/cm^3; ρ_s – density of soil particles, g/cm^3; ρ_{df} – density of the frozen soil skeleton, g/cm^3; W_f – frozen soil humidity, d.q.; W_p – moisture content at the limit of plasticity, d.q.; W_m – moisture of mineral particles, d.q.; I_p – plasticity number; i – ice content; h – thickness of the thawed layer, cm; e_f – coefficient of frozen soil porosity (frozen soil void ratio); k_1, k_2 – empirical coefficients (for sand $k_1 = 0{,}1$, for loam $k_1 = 0{,}05$; $k_2 = 0{,}8$); k_3 – coefficient of proportionality; k_4 – a correction empirical factor which takes into account the deviations of individual values of settlement from the average values, equal to 0.95 for loam and 1.3 for sandy soils; k_5 – empirical coefficient depending on the type of soil, moisture and compaction pressure.

The results of numerous studies of the phenomenon of permafrost soils thawing settlement show that the development of thawing deformations is determined by two components:

1. Instantaneous settlement due to the transition of pore ice into a liquid state and the destruction of the cryogenic structure of the soil.
2. Long-term settlement of thawed soil compaction due to the external load.

Subsequently, on the basis of the developed theoretical prerequisites and obtained experimental data many researchers carried out a calculated assessment of the deformations of permafrost soils thawing and proposed their own methods for solving this problem by numerical methods.

At the same time, most of the obtained dependencies involve the calculation of only the final value of the settlement after the completion of all physical and mechanical processes and stabilization of the foundation temperature regime without taking into account the time factor. However, in the process of thawing there is a continuous migration of moisture caused, among other things, by the formation of excessive pore pressure at the border of the thawing front which leads to the emergence of another component of thawing settlement – settlement in the process of filtration consolidation.

The problem of calculating the thawing settlement taking into account filtration consolidation is not devoted too many works. N.A. Protodiakonova proposed a numerical solution of the problem of thawing permafrost soils using the finite difference method with a number of restrictions on the applicability of the developed model [34].

At present, there is no uniform mathematical model that comprehensively describes the process of permafrost soils thawing. Existing calculation methods have a number of serious assumptions which do not make possible to use of the obtained solutions for various types of initial conditions for solving the problem, and also do not allow assessing the dynamics of the development of foundation deformations in time, thereby preventing the correctl assessment of building structures safety at any time in the conditions of changing temperature regime.

Peculiarities of soil SSS change during thawing. Features of moisture migration in thawing soils

According to on the results of studying the mechanisms of thawing deformations researchers have identified direct dependencies between physical and mechanical processes, occurring in the soil mass at the micro and macro levels, and the final values of deformation. A complex effect of changes in mineral composition and physical characteristics, that is density, ice content, porosity and voidness, humidity, permeability, consistency on the permafrost soils compressibility during thawing has been revealed.

First of all, there were made the attempts to explain the mechanisms of deformability by assessing changes in the structure of soil samples. By his studies E.J. Chamberlain has identified that for dispersed soils with a small amount of clay particles (for example, for sands and sandy loams) during freezing and thawing sand particles determine the compressibility of the soil as a whole due to contact with each other while smaller clay particles occupy a free pore space and affect only permeability. On the contrary, for dispersed soils with a high content of clay particles (for example, for loams and clays) in the process of freezing porosity significantly decreases and the structure of the soil becomes denser which is caused by the almost complete absence of contacts between large particles; all changes of soil properties in the process of freezing are based on the changes in the initially formed matrix of clay particles [16].

It has been experimentally recorded that deformation during thawing of frozen soils of the same genesis and similar mineralogical composition is distiguished for samples of different cryogenic structure. The shape, size and location of ice inclusions in the samples have a direct impact on the final compressibility of thawing soils [35, 36].

The distribution of thawing deformations in time is primarily determined by the characteristics of permafrost soils. The results of the studies are contradictory for soils of different types, structures and genesis, but in general they indicate an increase in soil permeability properties after thawing [37–39]. To define the contribution of filtration consolidation to the determination of the total deformation of the soil mass there were carried out studies of the pore pressure at the boundary of the samples thawing front. The results of N.A. Tsytovich's work show that there is no complete dissipation of pore pressure during thawing [40]. At the same time, the methods for determining excess pore pressure in thawing soils are not presented in existing studies, and the distribution of pore pressure in the unfrozen zone of thawing soil is taken according to approximate dependencies.

In addition, deformation of thawed permafrost soils are characterized by rheological deformation of the soil mineral skeleton (creep deformation) arising in the process of the secondary consolidation of soils. Various calculation models considering the development of creep deformation were obtained by S.S. Vyalov, M.N. Goldstein, A.A. Ilyushin [41–43].

Thus, based on the results of existing studies the following stages of the development of thawing deformations can be given acccent to (Fig. 5):

1. The beginning of destruction of the cryogenic structure of the soil.
2. Formation of excess pore pressure at the border of the thawing front.
3. The beginning of filtration consolidation of thawed soil, an increase of contact stresses arising between soil particles.
4. Dissipation of excess pore pressure, completion of the destruction of the cryogenic structure.
5. Beginning of secondary consolidation processes, stress relaxation in thawing soil.

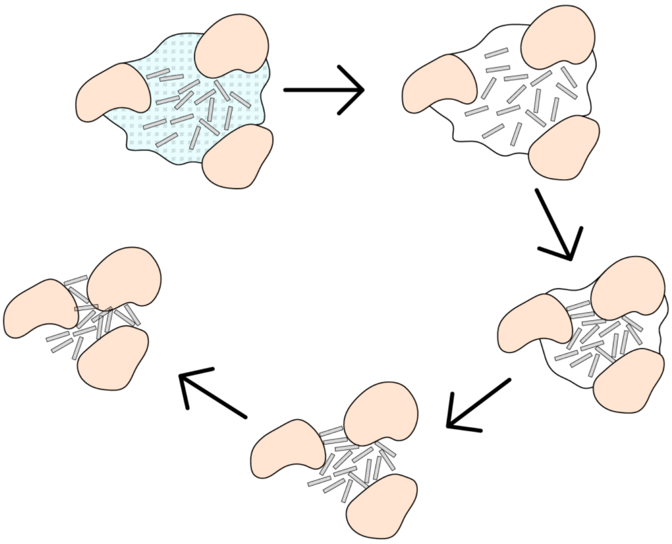


Fig. 5. Modern understanding of development stages of deformations of permafrost soils thawing
Рис. 5. Современное представление об этапах развития деформаций оттаивания многолетнемерзлых грунтов

Another factor which requires compulsory regard to the development of a calculation model of thawing foundations is the repeatedly recorded in the course of studies variability of the physical and mechanical properties of soils during thawing.

Revealed in the course of laboratory experiments, carried out by M.N. Tsarapov, R.A. Kotov and F.G. Bakulin, the decreasing of the strength and deformation characteristics of the soil foundation during thawing is caused by the structural change of the soil as a result of moisture migration in the process of cryogenic absorption [44].

According to the results of the research it was found that during thawing the redistribution of pore liquid in sands is insignificant even at high initial moisture content and this does not lead to a considerable change in strength and deformation characteristics during thawing. On the contrary, in clayey soils there is a significant decrease in the strength of thawed soil at the thawing boundary with the origination of excessive pore pressure in the contact layer [18, 25, 45]. For soils with a high content of clay particles and high initial moisture content (for example, for loam), a decrease in the value of shear resistance by up to 50 % has been identified. Modern studies also confirm such a sharp drop in strength during thawing under conditions of deviatory loading of samples (Fig. 6).

Based on the results of existing studies it has been revealed that the impact of freezing and thawing cycles leads to a general decrease in the strength and deformation characteristics of the foundations; at that, the degree of the decrease in strength and deformation characteristics depend on the indicators of consistency, porosity, density and natural moisture of the soil [17, 46].

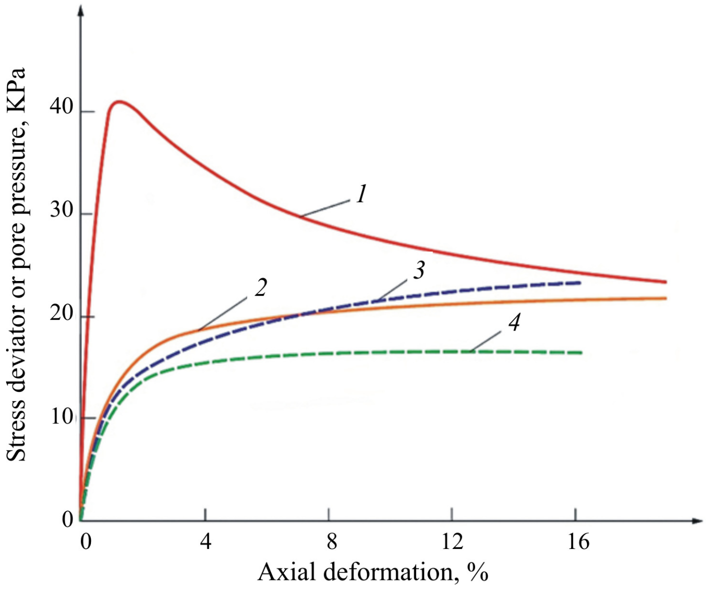


Fig. 6. Results of triaxial consolidated-drained tests of samples in the unfrozen state and the state after thawing: *1* and *3* – test results in the form of "deviator – relative deformation" dependencies for the sample in the unfrozen state and the state after thawing, respectively; *2* and *4* – the "pore pressure – axial deformation" dependency for the sample in the unfrozen state and the state after thawing, respectively (G.G. Boldyrev [46])

Рис. 6. Результаты трехосных консолидировано-дренированных испытаний образцов в незамерзшем состоянии и после оттаивания: *1* и *3* – результаты испытаний в виде зависимостей «девиатор – относительная деформация» для образца в незамерзшем состоянии и после оттаивания соответственно; *2* и *4* – зависимость «поровое давление – осевая деформация» для образца в незамерзшем состоянии и после оттаивания соответственно (Г.Г. Болдырев [46])

Solution of foundation thawing problems by numerical methods. Analysis of the existing permafrost thawing models

The complexity of physical and mechanical processes and phenomena occurring in the soil foundation during its freezing and thawing predetermines the solution of such problems by numerical methods using software complexes implementing the method of finite elements [47–49].

At the same time, the use of numerical methods allows taking into account all external factors affecting the structure in the most accurate way by simulating the boundary conditions of the problem, including the dependence of temperature changes on time, which is almost impossible to implement using strict analytical solutions [50, 51].

A mathematical description of the processes of a soil mass freezing and thawing can be described by thermal conduction equations for a non-stationary thermal regime in three-dimensional space, the system of which has the form of Stephan's problem [52]:

$$\rho_d\left(C_{th(f)}+L_0\frac{\partial W_w}{\partial T}\right)\frac{\partial T}{\partial t}=\sum_{i=1}^{3}\frac{\partial}{\partial x_i}\left(\lambda_{th(f)}\frac{\partial T}{\partial x_i}\right)+q_v \tag{14}$$

where $C_{th(f)}$ – specific heat capacity of soil (thawed or frozen) (kJ/kG·K), ρ_d – dry soil density (kG/m^3), T – temperature (°C), t – time (s), $\lambda_{th(f)}$ – thermal conductivity of soil (thawed or frozen) W/(m·°C), x,y,z – coordinates (m), q_v – capacity of internal heat sources (W/m^3), $L_0=335\cdot10^6\ \text{J}/\text{m}^3$ – heat of water-ice phase transformations, W_W – moisture of frozen soil at the expense of unfrozen water.

The solution of the Stephan problem is carried out on the basis of the determination of the incoming and outgoing heat flux from the elementary volume of the soil by the search for the value of energy transfer from the equations of thermal conduction with reference to the energy balance at the boundary of the phase transition called the Stefan condition. At that, the so-called "latent heat of phase transitions" – the amount of heat absorbed or released by the soil mass in the process of phase transformations of pore moisture into ice and vice versa is considered in the process of solution. The initial data for solving the problem is a set of thermophysical characteristics determined in the course of laboratory studies or by means of specialized analytical solutions [53, 54].

Existing numerical solutions for the problem of determining thawing deformations, as a rule, solve the problem of settlement of the soil mass in two stages: first, by determining the temperature state in each elementary node of the design scheme, and then, on the basis of the constructed temperature fields in the soil mass by determining the quantitative values of thawing settlement in each node of the scheme. The disadvantages of this approach are the impossibility of taking into account the mechanism of changing the mechanical characteristics of the soil mass in the process of thawing and the impossibility of calculating deformations in time.

Modern representations of the numerical solution of the problem of thawing of a soil mass can take into account various mechanisms of behavior of frozen soils during thawing: for example, the model of freezing and thawing soil proposed by S.A.G. Amiri implements thawing deformations with the calculation of elastic dilatant deformations due to the process of moisture migration in the soil, volumetric deformations of compaction developing in the process of consolidation of frozen soils, and, finally, plastic deformations which arise when the tensile strength in the soil mass is exceeded [55].

$$\varepsilon=\varepsilon_{me}+\varepsilon_{se}+\varepsilon_{mp}+\varepsilon_{sp}, \tag{15}$$

where ε_{se} – elastic dilatant deformations due to the process of moisture migration in the soil, calculated by the formula:

$$d\varepsilon_{se} = \frac{k_s}{3(1+e)} \cdot \frac{dS}{S - p_{at}} I, \tag{16}$$

where ε_{sp} – plastic dilatant deformations arising as a result of the process of moisture migration in the soil

$$d\varepsilon_{me} = \frac{k}{1+e} \cdot \frac{dp^*}{p^*}, \tag{17}$$

where ε_{me} – elastic deformations of compaction calculated by the formula:

$$d\varepsilon_{mp} = \frac{\lambda - k}{1+e} \cdot \frac{dp_y^*}{p_y^*}, \tag{18}$$

where ε_{mp} – plastic deformations of compaction calculated by the formula.

At that, even modern complex models for determining thawing deformations use non-universal empirical coefficients in their own mathematical dependencies, what does not allow using and applying these models in conditions of sharp differences in the genesis and type of soils used for the development of the model and located directly on the site of the proposed construction of the designed structures.

Conclusion

1. Construction in areas of permafrost is associated with the presence of additional risk factors primarily related to a possible change in the temperature regime of permafrost soil foundations in the process of construction or operation of raised structures and the subsequent development of deformations of frozen soils thawing under the structure.
2. At present, there is no uniform mathematical model which comprehensively describes the process of permafrost soils thawing. The existing calculation methods have a number of serious assumptions not making possible the use of the obtained solutions for various types of initial conditions for solving the problem, and also not allowing the assessment of the dynamics of foundation deformations development in time, thereby not allowing to correctly assess the safety of buidings and structures at any time under changing temperature conditions.
3. The complexity of physical and mechanical processes and phenomena occurring in the soil foundations during their freezing and thawing predetermines the solution of such problems by numerical methods using software complexes which implement the method of terminated elements.
4. The existing numerical solutions to the problem of determining thawing deformations, as a rule, solve the problem of settlement of the soil mass in two stages: first, by determining the temperature state in each elementary node of the design scheme, and then, on the basis of the constructed temperature fields in the soil mass, by determining the quantitative values of the thawing settlement in each node of the scheme. The disadvantages of this approach are the impossibility of taking into account the mechanism of changing the mechanical characteristics of the soil mass in the process of thawing and calculating deformations in time.
5. Modern integrated models for determining thawing deformations use non-universal empirical coefficients in their own mathematical dependencies, which does not allow using and

applying these models in conditions of sharp differences in the genesis and type of soils used for the development of the model and located directly at the site of the proposed construction of the designed structures.

6. Based on the results of existing studies the following stages of development of thawing deformations can be distinguished: the beginning of the destruction of the cryogenic structure of the soil, the formation of excess pore pressure at the border of the thawing front, the beginning of filtration consolidation of the thawed soil, the increase in contact stresses arising between soil particles, the dissipation of excess pore pressure, the completion of the destruction of the cryogenic structure, the beginning of secondary consolidation processes, relaxation stresses in thawing soil.

7. In order to ensure the reliability and safety of structures raised on permafrost soils it is proposed to create a universal model of thawing soil, which allows taking into account changes in the physical, mechanical, and filtration characteristics of the soil foundation in the process of thawing and allows solving the problem of thawing in time, with the determination of the specific value of deformations in the process of filtration consolidation of thawing frozen soil.

Финансирование. *Исследование не имело спонсорской поддержки.*
Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*
Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации.*

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