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Frost cracks formation in permafrost regions

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Abstract. The object of the study is the soil susceptible to cryogenic cracking during freezing. The formation of cracks creates the problems in the development of mineral deposits in northern regions with sharply continental climates in Europe, Asia and North America. The destructive effects of cracks on the construction of roads and linear structures require the prediction of cryogenic cracks. The developed mathematical model and the method of its use provide the prediction of the processes of frost cracks formation in harsh climates. The calculation algorithm realizes the procedures for the step-by-step solution of the spatial strength problem for a fragment of a soil mass taking into account changes in temperature fields and physical and mechanical properties of frozen soils over time. The given example demonstrates the results of predicting of cryogenic cracking of the soil in the form of graphs of stress distribution in the freezing massif. The calculation results illustrate the ability to predict the formation of frost cracks, the ability to determine the main parameters and periods of cracking. The research results can be used in the design of objects in the conditions of propagation of soils subjected to cracking.

1. Introduction

The object of research is a massif of frozen soils subjected to cryogenic cracking in cold regions. In articles [1–3] permafrost propagation zones in the Northern Hemisphere were identified. In [4, 5], the studies devoted to modeling changes in the permafrost occurrence area and changes in soil characteristics over time are presented. The consequences of cryogenic soil cracking are observed in the form of special relief forms during the formation of cracks and polygons in natural conditions on the Earth's surface, during the formation of ice wedges. This is confirmed by field observations in Siberia, Alaska, Canada, the European North and several other regions [6–10].

Most often, cracks occur in areas with a sharply continental climate, with a low negative average annual air temperature, with large amplitudes of annual air temperatures, with a small thickness of snow cover, on the slopes [11, 12]. The formation of cryogenic cracks is also noted in territories with seasonally freezing soils. The size of the seasonally thawed layer in such regions can reach 2-3 meters or more. The average monthly temperature of frozen rocks, for example, in the Central Transbaikalia can decrease at a depth of 2 m to –8 °C, at a depth of 6 m – to –4 °C [13, 14]. The listed factors affect the nature and magnitude of temperature stresses and strains. In this case, cracks form at approximately equal distances from each other in mutually perpendicular directions. So-called "polygons" that are similar in shape to rectangles are formed. The dimensions of "polygons" depend on moisture and other properties of soils, on the dynamics of changes in air temperature. With an increase in the strength of the near-surface soil layer, the size of the polygons increases.

The relevance of this study is due to the fact that the northern regions of our planet are distinguished by large reserves of minerals. Development of regions is complicated by a number of problems associated with the natural conditions of the regions [14, 15]. Among the problems, one can distinguish such a phenomenon as cryogenic cracking. The formation of frost cracks in the soil creates serious difficulties in the operation of roads [16], long linear objects (pipes, cables), which are located underground [14]. There is a threat of damage to objects; the appearance of cracks provokes the formation of ground icing [12]. Thus, the relevance of studying the problem is associated with the influence of frost cracking of the soil on tecnogenic objects. There is a need for reliable forecasting of crack formation and taking these phenomena into account when designing objects in the northern regions.

Prediction of the processes of cryogenic cracks formation is based on previous studies in a number of directions of research reflected in the world literature. Crack formation processes are closely related to the laws of soil temperature changes. As the initial data for modeling cracks, we used the results of a study of the dynamics of soil temperature in the Northern regions during freezing and thawing [15, 17–21]. A number of authors have previously established the properties of frozen soils [22–25], including their strength characteristics [26, 27]. There are known studies of temperature deformations of soils with different properties at negative temperatures, not accompanied by the formation of frost cracks [28–30].

The most important element in predicting the process of fracture of porous materials and cracks formation is mathematical modeling. From publications devoted to modeling cryogenic cracks, we can distinguish works that use simple formulas. One of the first crack modeling schemes proposed by B.N. Dostavalov and S.E. Grechishchev, are given in article [12]. Criteria for the formation and individual parameters of cracks here are determined by approximate empirical formulas. A key factor in such techniques is the magnitude of the decrease in soil temperature in relation to its average annual temperature. As a condition for the formation of a cryogenic crack, the excess of temperature stresses in the massif over the breaking stress is considered. The possibility of cracking and their parameters is established depending on the properties of frozen soils, which vary in each case.

The simple analytical expressions of stresses in the soil are used in a number of modern publications [14, 31, 32]. In [14, 31], the authors propose to consider frozen soil as a linearly deformable material. Based on the solution of the thermoelasticity problem for half-space, in [31, 32] simple expressions are formed to calculate the stresses in soil massif, to determine the conditions for crack formation and their parameters. At the same time, the number of arguments in the applied empirical formulas remains insignificant. The joint solution of the spatial problem of heat and mass transfer and geomechanics makes it possible to use a much larger number of physical-mechanical and geometric parameters, climatic characteristics. This should provide a more objective assessment of the development of processes in the soil, since each of the factors can become decisive when the condition for the formation of a crack is met.

In article [11] a model of frost cracking was presented for a particular problem under conditions of the development of a slope process. Here, one-dimensional simplified heat transfer equations are used. The model is based on ice segregation in a previously formed crack, which can be considered as a secondary phenomenon. The probability of cracking during seasonal freezing in the absence of permafrost is confirmed. The occurrence of horizontal cracks and methods for their mathematical modeling in connection with the formation of lenses during ice segregation are considered in [23, 33]. In relation to the problem being solved, the interest here is the criteria for the rupture of frozen soil during its freezing.

The application of the finite element method to modeling the processes of freezing and thawing in known articles is usually limited to solving one-dimensional or two-dimensional problems [33–35]. In publications [33, 34], vertical displacements of the soil surface are determined when horizontal ice lenses are formed in soil massif. In article [35], channel slope deformations during freezing were studied using the finite element method in the framework of solving a two-dimensional problem. In [13], the purpose of research is to assess the effect of previously formed frost cracks in the soil mass on heat and mass transfer processes in a separate soil block located between the cracks. In this case, the role of external factors of influence on the strength and deformation characteristics of frozen soil used as the foundations of structures is established. When calculating the thermal regime in the soil block, two-dimensional heat conduction equations are used. Deformations and stresses in soil blocks are determined when solving a plain problem for a linearly deformable medium. Thus, the criteria and parameters of the formation of emerging frost cracks in the last presented works are not determined. When predicting frost cracks, preference should be given to solving the spatial problem. This makes it possible to take into account the redistribution of internal stresses (taking into account Poisson's ratio), temperature and moisture flows in the elements of the design scheme along the directions of the three coordinate axes. This approach makes it possible to use the available results of long-term meteorological observations, the traditional and obligatory list of materials obtained as a result of engineering-geological surveys as initial data.

The presented literature review confirms the absence of solutions to the spatial problem for assessing the formation of vertical frost cracks, taking into account the whole complex of external factors and the dynamics of the process under study. The purposes of the work are to estimate the possibility of cryogenic cracking of frozen soil, to develop a method for predicting the formation of cracks for various geological and climatic conditions. Within the framework of the indicated problem, the following tasks are solved. A correct mathematical model of the formation of cryogenic cracks in frozen soil is formed. A methodology for using the model is being developed; an analysis of the results is performed. To implement the tasks, the finite element method and three-dimensional elements of the soil massif are used. The calculation model includes the solution of the nonlinear problem of heat and mass transfer, the nonlinear problem of deformation of the soil mass taking into account the dynamics of the development of processes in time.

2. Methods

A soil massif with specified physical and mechanical properties during the formation of cryogenic cracks is considered. The process of thermal deformations studying is divided into 2 stages. At the first stage, the dynamics of changes in temperature fields in the soil mass is determined based on the temperature field model. The air temperature forecast is formed on the basis of the results of long-term weather observations. The temperature distribution near the surface of the soil massif is determined by the climatic conditions of the region [20]. The temperature in the near-surface part of the soil half-space is determined by solving the non-stationary problem of heat and mass transfer. The solution of the equations of heat and mass transfer determines the values of temperature drops in the elements of the soil mass. At the second stage the methods of mechanics of a continuous medium are applied. The obtained values of temperature drops are included in the composition of the load vector at the stage of determining deformations and stresses in the soil mass using the software package “Lira”. In this case, temperature drops are parameters for loading the soil massif.

The algorithm for solving the problem of thermomechanics is presented in Fig. 1 as a combined mathematical model. The formation of a combined model begins with the establishment of the geometric dimensions and physico-mechanical properties of the studied soil masses. The composition of the model includes the climatic influences model, mathematical models of heat and moisture transfer processes, models of changes in the stress-strain state in rocks. In connection with the increase in the number of factors during the selection of parameters, the significance of factors is estimated by the correlation analysis method.

The most important element of the combined model is the mechanism for adjusting the basic physical and technical parameters of soils at each calculation step at given intervals. Fig. 1 lists the main mutual functional dependencies of the parameters implemented in the model. The dependences of temperature and humidity at individual points of the soil massif on the thermal conductivity and heat capacity of the soil are taken into account at the stage of solving the heat and mass transfer problem. The thermal conductivity and heat capacity at each step are adjusted as a function of humidity of the soil mass. Thermal deformations are determined taking into account the changing of coefficients of linear expansion, soil temperature and deformation modulus. The linear expansion coefficient is adjusted at each step as a function of temperature.

Another important feature of the technique is the use of a spatial model. The use of such a model provides accounting for heat transfer and moisture transfer in the direction of three coordinate axes, redistribution of stresses and deformations in three directions. When solving the spatial problem, the laws of the theory of elasticity and plasticity, the laws of heat and mass transfer in porous media are used. An increase in the total number of arguments in these dependencies in comparison with the use of empirical formulas is intended to ensure greater reliability of the results obtained.

The finite element method is applied. Multiple solution of the problem of continuum mechanics in changing conditions is performed using the modern software package “Lira”. A three-dimensional soil model is formed from spatial finite elements into which a soil massif with variable parameters is divided. The use of volumetric finite elements allows to assign different properties to each of the finite elements at different time intervals. A fragment of the section according to the calculation model of the soil massif with a breakdown into finite elements is shown in Fig. 2. The movement of the soil mass at the boundaries of the studied model is limited by the installation of links in nodes at the outer contour of the massif.

The change in temperature fields in the soil mass at the considered time intervals is determined on the basis of the theory of unsteady heat and moisture transfer [36]. The transfer of heat and moisture in the soil is described by differential equations:

$$\frac{\partial T}{\partial \tau} = \nabla\left(a \cdot \nabla T\right) + \frac{c_w \cdot \left(D_w \cdot \nabla W + D_w \cdot \delta \cdot \nabla T\right) \cdot \nabla T}{c} + \frac{\varepsilon \cdot L}{c \cdot (1-\varepsilon)} \cdot \frac{\partial W}{\partial \tau} + \frac{q_v}{c \cdot \rho_d}; \quad (1)$$

$$\frac{\partial W}{\partial \tau} = D_w \cdot \nabla^2 W + D_w \cdot \delta \cdot \nabla^2 T - \varepsilon / \left(1-\varepsilon\right) \cdot \frac{\partial W}{\partial \tau} + \frac{\partial K_w}{\partial y}, \quad (2)$$

where T is soil temperature, °C;

W is soil humidity, %;

y is vertical coordinate, m;

τ is time, s;

c is specific thermal capacity of a soil, J/(m³·°C);

ε is phase transition criterion;

L is specific heat of ice crystallization, J/kg;

D_w is coefficient of diffusion of moisture, m²/s;

δ is thermogradient coefficient, 1/°C;

$a = \lambda / (c \cdot \rho_d)$ is coefficient of thermal diffusivity, m²/s;

λ is specific thermal conductivity of a soil, W/(m·°C);

ρ_d is density of a dry soil, kg/m³;

q_v is density of internal thermal sources or heat sinks, J/(m³·h);

c_w is heat capacity of water, J/(m³·°C);

K_w is moisture transfer coefficient, m/s;

ρ_w is density of water, kg/m³.

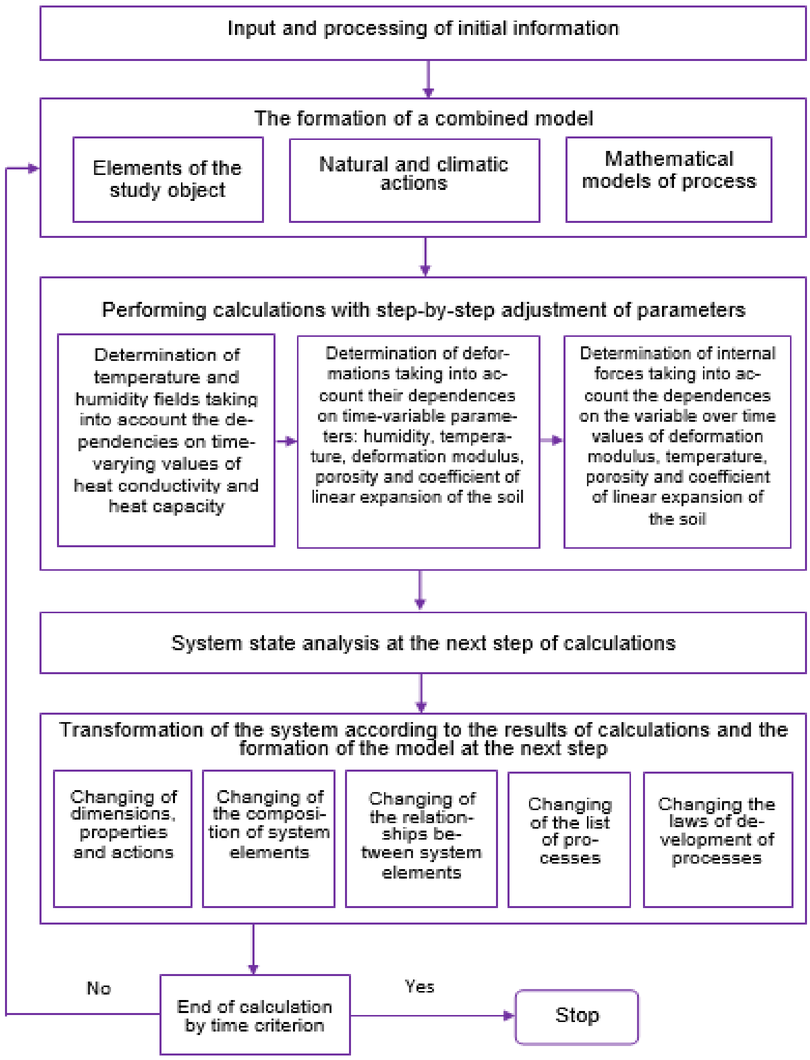

Figure 1. Scheme of dynamic modeling of the development of processes in the soil.

Moisture transfer in the saturation zone, if it presents, is described by the well-known filtration equation.

The heat balance equation is used in the form:

$$\lambda \cdot \frac{\partial T}{\partial y} + (1 - A)\left[q_p^s(\tau) + q_r^s(\tau) \right] - q_1^s(\tau) - q_k(\tau) - q_i(\tau) = 0, \quad (3)$$

where A is surface albedo;

$q_p^s(\tau)$ and $q_r^s(\tau)$ is thermal flow conditioned by direct and scattered solar radiation to the surface, respectively, J/m²·s;

$q_1^s(\tau)$ is effective surface radiation, J/m²·s;

$q_k(\tau)$, $q_i(\tau)$ are thermal flow conditioned by convective transfer and evaporation, respectively, J/m²·s.

The moisture balance equation is formed on the basis of the expressions given in [2, 4]. As a result, the conditions for the movement of moisture into the soil are proposed to be represented in the form:

$$\Delta W_{\text{lay}} = I_{\text{kr}} - G, \text{ if } I \geq I_{kr}; \quad \Delta W_{\text{lay}} = X - S - E - G, \text{ if } I < I_{\text{kr}}; \quad (4)$$

$$G = -D_w \cdot \left(\frac{\partial W}{\partial y} + \delta \cdot \frac{\partial T}{\partial y} \right) - K_w. \quad (5)$$

In this case, the amount of moisture supplied to the surface I and the limiting amount of moisture that can be absorbed per unit of time I_{kr} are determined from the expressions

$$I = X - S - E, \; I_{\text{kr}} = \frac{q_{\text{w}}}{\rho_{\text{w}} \cdot \Delta\tau}, \quad (6)$$

where X is moisture inflow from outside, m / s;

G is the intensity of movement of moisture under the influence of gradients of temperature, humidity and gravitational forces, m / s;

S and E are the intensity of runoff and evaporation of moisture, m / s;

q_{w} is the maximum absorption rate during the time $\Delta\tau$, determined by the formula of I.A. Zolotar, kg/m²;

ΔW_{lay} is change in moisture content in the soil layer, m / s.

The resolving heat and moisture transfer equations take into account: heat transfer due to diffusive moisture transfer, phase transition criteria, moisture transfer caused by a temperature gradient, gravitational component of moisture transfer. The heat balance equation on the surface takes into account effective radiation, direct and scattered solar radiation, and heat fluxes associated with convective transport and evaporation. The moisture balance equation in the model takes into account evaporation, moisture movement associated with runoff and absorption of precipitation on the surface, moisture movement caused by the action of gravitational forces, temperature and humidity gradients. The interrelation of the constituent elements of heat and moisture balances is taken into account. The features of heat and moisture transfer associated with the presence of two fronts of freezing are taken into account. The mathematical model of heat and mass transfer used provides for the correction of parameters such as specific heat, thermal conductivity, moisture transfer coefficient, and others due to changes in soil temperature and humidity. Parameters are adjusted in the nodes and elements of the model over time. As a result, at each time interval, the model adapts to changing boundary conditions and the properties of its elements.

At the stage of determining temperature deformations, the methods of continuum mechanics are applied. Initial information about the model includes the physicomechanical characteristics of the constituent elements of the soil mass, temperature gradients. When determining the internal forces in the soil mass, the dependences of the deformation modulus and the coefficient of linear expansion on temperature are taken into account. Long-period temperature fluctuations at which stresses can reach the ultimate of long strength are taken into account. In the course of solving the problem of thermoelasticity using the software package «Lira», at lowering the temperature with a given step, the values of tensile stresses in the freezing soil mass are established. At some step, tensile stresses reach the breaking stress. In the soil model, a crack is formed by removing bonds between the finite elements of the soil massif in the near-surface layer. A further decrease in temperature in the algorithm for solving the problem is realized, and the thermoelasticity problem is solved repeatedly within a given time interval. Redistribution of stresses in the soil massif is reevaluated. The end of calculations is determined by the criterion of reaching the boundary of a given period of time.

3. Results and Discussion

During numerical experiments, temperature and stress fields in the soil mass were studied for the Central Transbaikalia region. A part of a half-space with dimensions in plan 50×50 m and a height of 5 m is considered as a design model. Using a larger part of the massif does not change the calculation results. The image of such an object is not informative, therefore it is not given, and further fragments of sections drawn through the half-space are used. The finite elements are prisms with dimensions in plan 1×1 m and heights of 0.25 and 1 m.

The following boundary conditions are used. When solving the problem of heat and mass transfer, the temperature and humidity on the lower edge of the considered massif are taken constant. On the lateral faces, the conditions of symmetry of these parameters with respect to the faces are used. At the second stage, when solving the problem of geomechanics, at the boundaries of the massif, at the nodes of the finite element grid, links are established that are perpendicular to the planes that bound the soil massif.

The time step for the problem of heat and mass transfer is taken equal to 4 hours, for the problem of geomechanics – 24 hours. A freezing soil massif composed of clay loam with a density of γ = 1.8 g/cm^3 a Poisson's ratio of 0.3 and humidity W = 20 % is considered. The specific thermal capacity and the thermal conductivity of the soil in the thawed state are, respectively, c = 2.48·10-6 J/(m^3·°C), λ = 1.1 W/(m·°C). Density of a dry soil ρ_d = 1400 kg/m^3; coefficient of diffusion of moisture D_w = 2.8 ·10^{-8} m^2/s; moisture transfer coefficient K_w = 0 m/s. Climatic characteristics are taken according to SP 131.13330.2018 Construction climatology and the meteo.ru website. Variable characteristics of the frozen soil were taken as a function of temperature in each finite element of the model using the materials presented in SP 25.13330.2012 Bases and foundations on permafrost and in works [22, 24, 25, 27, 29, 37, 38].

The mechanism of cracking is due to a decrease in the volume of the soil as a result of its temperature reduction during cooling. The stresses caused by the temperature drop in the frozen soil massif are determined when solving the geomechanics problem using the software package “Lira”. Researchers of this problem traditionally consider the ultimate of long-term tensile strength as a criterion for the formation of cracks. The calculated stresses in each soil layer are compared with the ultimate of long-term tensile strength. If these stresses in the layer exceed the long-term strength limit, a crack is formed in the layer. For the soil considered in the example, the long-term strength limit is 259 kPa. When the stress reaches this value in the layer, a rupture occurs.

Based on the results of the first stage of solving the problem, the fields of temperature and humidity are formed in the half-space and the physical and mechanical properties depending on them are corrected. The tables 1 and 2 shows the average parameters for each of the layers into which the soil massif is divided in the vertical direction at key stages in the development of processes associated with the formation of cracks. These parameters are included in the equilibrium equations solved by the finite element method using the software package “Lira” and are the initial data for determining the stresses and deformations in the considered soil mass by this software package.

As a result of the calculations, the displacements of all nodes of the finite element network and the internal forces in the elements of the soil model are determined. In the process of lowering the temperature of the air and the upper layers of the soil massif, on November 5, tensile stresses reach 259 kPa in the near-surface layer of the soil. Fig. 2 shows a mosaic of stress distribution on the eve of cracking. The corresponding characteristics of soil elements are given in Table 1. The distance between the horizontal lines in all figures is 0.25 m in the near-surface layer and 1 m in the layers lying below, between the vertical lines – 1 m. As can be seen from the table and graphs, tensile stresses reach the breaking stress in the upper zone of the soil mass, taken in the calculations equal to 259 kPa [22, 27]. In the second layer from the surface, tensile stresses remain insignificant and reach 112 kPa. This is due to the small temperature difference in the indicated area. For this reason, at a depth of more than 0.25 meters, soil rupture for a given period of time is not predicted according to the results of calculations. Cracks are formed in the upper layer.

The distance between cracks depends on the modulus of deformation, Poisson's ratio, density, moisture content, coefficient of linear expansion of the soil, temperature gradient. The criterion for determining the distance between cracks is the absence in the upper soil layer of areas with tensile stresses exceeding the ultimate tensile strength of the soil after cracking. For soil with the physical and mechanical parameters considered in the work, this distance is 3 meters. With a larger distance between the cracks, this condition will not be met. The achievement of this condition is checked at the stages of lowering the temperature of the massif in the course of calculations.

After the formation of cracks in the near-surface layer of the soil, the nature of the stress distribution in the massif changes, and the characteristics of the soil are preserved. Fig. 3 shows a mosaic of stress distribution in the soil after the formation of cracks. For better demonstration of the results, only typical fragments of the model in the area of crack formation are highlighted in the figures. As can be seen from the graphs, the magnitude of tensile stresses after the formation of cracks in the near-surface layer decreases and amounts to 253 kPa. Redistribution of stresses in the layers of the soil massif located below is noted. In the second row of finite elements from the top, the average stresses are 126 kPa. In the third row, the influence of location of cracks on the nature of stress distribution is noted. Directly under the cracks, the stresses are 63 kPa; in the zones remote from the cracks, they approach zero. Here, a decrease in stresses occurs as a result of a redistribution of the load on the layers lying above. The crack opening width is about 1 cm. The tensile stresses at the surface after the formation of cracks remain below the ultimate strength of the soil.

With a further decrease in soil temperature on November 26, tensile stresses in some areas of the massif again reach the limit of long-term strength of the soil. Such areas are highlighted in Fig. 4 with a dark tone and are located in the second row of finite elements from the surface. Average stresses in the upper and third layers from the surface do not exceed 129 kPa. The characteristics of the soil are presented in Table 2.

In weakened sections, the cracks continue to deepen, and already the second row of finite elements in the model is subject to rupture. The nature of stress distribution in the elements is shown in Fig. 5. After the development of cracks in depth, unloading zones with stresses up to 48 kPa are observed near the cracks in the upper row of soil elements. At the same time, stresses of about 96 kPa remain in the middle part of the polygons. In the second layer weakened by cracks, the stresses decrease to 192 kPa. Under the cracks, due to the weakening of the section, the load is taken by the elements of the third row, where the stresses reach 168 kPa. In the elements at some distance from the cracks, the stresses in the third layer decrease to 120 kPa. In a soil massif that does not experience large temperature drops, tensile stresses remain small.

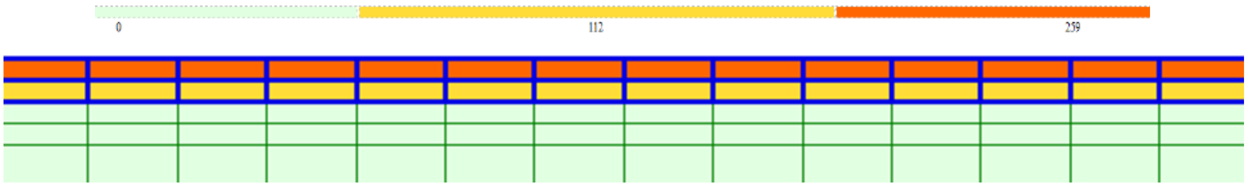

Figure 2. Distribution of stresses in the soil massif as of November 5 before crack formation (The numerical values on the color scale are given in kPa).

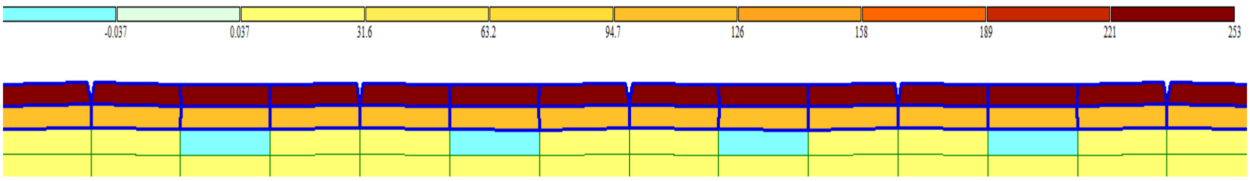

Figure 3. Distribution of stresses in the soil massif after the formation of cracks (The numerical values on the color scale are given in kPa).

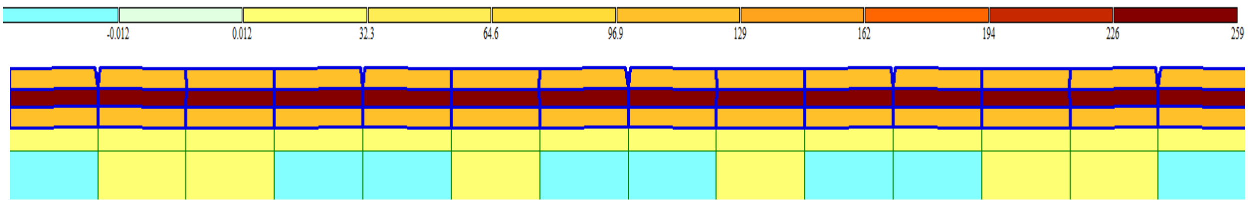

Figure 4. Distribution of stresses in the soil massif after the formation of cracks and with a further decrease in temperature as of November 26 (The numerical values on the color scale are given in kPa).

Table 1. Soil characteristics at different depths of the massif as of November 5.

Layer number	Layer thickness, m	Depth of the bottom of the layer, m	Average temperature in the layer, °C	Temperature difference in the layer, °C	Deformation modulus, MPa	Coefficient of thermal expansion, 10^{-6} (°C)$^{-1}$	Maximum stress in the soil massif, kPa	
							Before cracking	After the formation of cracks
1	0.25	0.25	-8.2	-7.7	160	150	259	253
2	0.25	0.5	-3.3	-2.8	150	190	112	126
3	0.25	0.75	-0.5	0	25	380	0	63
4	0.25	1	-0.5	0	25	380	0	63
5	1	2	-0.5	0	25	380	0	0
6	1	3	-0.6	-0.1	25	380	0	0
7	1	4	-1	-0.5	25	380	0	0
8	1	5	-1.1	-0.6	25	380	0	0
9	1	6	-1.2	-0.7	25	380	0	0

Table 2. Soil characteristics at different depths of the massif as of November 26.

Layer number	Layer thickness, m	Depth of the bottom of the layer, m	Average temperature in the layer, °C	Temperature difference in the layer, °C	Deformation modulus, MPa	Coefficient of thermal expansion, 10^{-6} (°C)$^{-1}$	Maximum stress in the soil massif, kPa	
							Before cracking	After the formation of cracks
1	0.25	0.25	–17.6	–17.1	170	30	129	96
2	0.25	0.5	–8.4	–7.9	160	150	259	192
3	0.25	0.75	–3.5	–3	150	190	129	168
4	0.25	1	–2.4	–1.9	150	190	65	48
5	1	2	–1	–0.5	25	380	0	0
6	1	3	–0.5	0	25	380	0	0
7	1	4	–0.7	–0.2	25	380	0	0
8	1	5	–1	–0.5	25	380	0	0
9	1	6	–1.2	–0.7	25	380	0	0

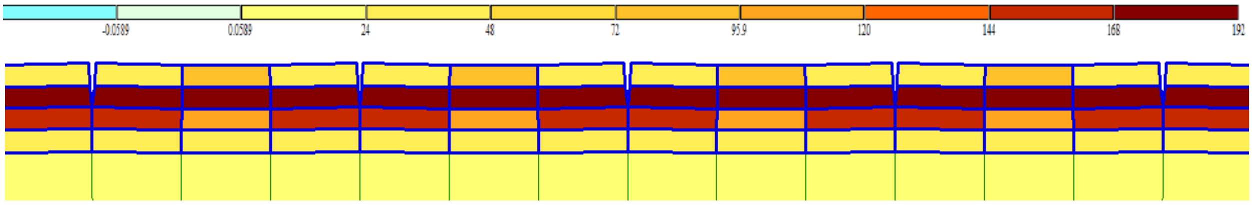

Figure 5. Distribution of stresses in the soil massif after deepening cracks up to 0.5 m (The numerical values on the color scale are given in kPa).

To evaluate the effectiveness of the used model of cryogenic cracking, the author compared the results obtained with the results obtained previously for similar conditions by the methods of Grechishchev and Dostalov and with the observations of these authors [12]. In both cases, the results establish the likely formation of cracks in November with an opening width of about 1 cm. The obtained parameters of crack formation correspond to the results of observations in the region in open areas without snow cover [12]. The advantage of the proposed method lies in the fact that in addition to determining individual parameters of cracks formation (opening width, distance between cracks); time factors are taken into account. There is an opportunity to track the dynamics of the processes of deformation of the soil massif over a given period of time under various variants of climatic influences.

The models of frost cracking under consideration have a wide range of uses. They can be applied in practice when predicting their possible development in regions with sharply continental climate, where this phenomenon is common. Such estimates are of great importance in the construction of roads, airfields, hydraulic structures, pipelines and other engineering facilities. Crack formation models can also be used to predict the ground icing formation.

4. Conclusions

1. A mathematical model of the formation of cryogenic cracks in the soil mass has been formed, It reflects the thermomechanical and geomechanical processes in the freezing soil, taking into account the dynamics of their development. The mathematical model is distinguished by the use of the finite element method and three-dimensional elements of the soil massif, periodic adjustment of the model parameters in conditions changing with time.

2. A methodology to assess the likelihood of cryogenic cracks formation in the conditions of continuously changing soil parameters and external influences over time has been developed. In contrast to the known techniques, the joint solution of the problems of geomechanics and heat and mass transfer as part of the spatial problem allows one to take into account the redistribution of internal forces, temperature and moisture flows in the soil mass along the directions of three coordinate axes. The advantages of the methodology are the adjustment of parameters, the use of a large number of parameters in comparison with other known methods, the use of soil characteristics in the model, traditionally obtained during engineering and geological surveys.

3. Based on the results of calculations, the nature of the distribution of stresses in the massif at different stages of the formation and development of frost cracks at the soil surface was established within the selected dimensions of the soil layers and the time step. The resulting displacements of nodes and internal forces in the elements presented in sections drawn through the middle of the polygons take into account the dynamics of the formation of cracks in the soil mass within a given period of time. The analysis of the obtained results confirms the possibility of predicting the formation of cryogenic cracks and determining their parameters in the northern regions by the proposed method. The obtained results of predicting the cryogenic soil cracking in November are consistent with observations in the region.

4. Since the formation of cracks poses a threat of damage to objects, the values of temperature deformations and stresses arising from this, of course, should be taken into account in the design calculations as a temporary load in the conditions of permafrost propagation in regions with low temperatures. The proposed technique allows to prevent the threat of damage to objects.

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