Frost Weathering as a Process of Degradation of Surface of Rocks under the Action of Internal Stresses

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Abstract. The article presents the results of studies of self-organization of ice inclusions in the surface layer of frozen moisture-bearing rocks. Frosty weathering of rocks is determined by the formation of inhomogeneous stresses in the surface layer. They are due to the random nature of the appearance of crystallization centers and further inhomogeneous growth of crystalline (ice) formations. They are narrow, rectangular inclusions of fixed sizes for which solutions of the theory of elasticity are known. An original model of heat and mass transfer in the surface layer of a moisture-containing rock under the influence of variable temperatures with a period of ~ 12 hours is used. The correlated arrangement of crystalline formations is determined by the process of minimizing the total elastic energy of the ensemble of ice formations depending on the angle of their mutual orientation

1. Introduction
The detachment of thin scales from the surface of rocks is an important geomorphological process of erosion, operating in a wide range of rock types and climatic conditions. The main processes that lead to spallation and detachment are variable depending on the structure of rocks and climate. At the same time, among the most likely reasons, periodic changes in moisture content and temperature in the surface layer of the rock are believed. For porous rocks located in temperate regions, spallation or detachment is due to the mechanisms of pore moisture freezing, crystallization and hydration of salts [1,2] or the formation of thermal stresses [3-8]. Weathering processes cause important changes in rock porosity. In addition to porosity, the distribution of pore sizes [9,10] is essential for identifying changes in the process of weathering of rocks. A change in the porosity from 0.25% to 0.62%, and an almost 50% decrease in the Young's modulus [11,12] is noted. Other studies have also shown that the parameters of the material, especially the geometry of pores and cracks, are very important for evaluating the behavior of the rock weathering process [13,14].

Understanding the causal mechanisms responsible for splitting off or detachment allows us to establish the evolution of erosion processes and landscape changes [15]; predict the degree of degradation of rocks, building stone materials [16-20].

In articles [21–24], it was established that fast processes, including wind and cloud cover, act on the cooling of rocks and cause their cracking. In [25], a summary of the results of five-year observations showed that the rate of destruction of bedrock is usually much higher during the freezing-thawing period from October to next May than in the frost-free period from June to September. Based on the predictive empirical model, the authors found that the rate of destruction depends on the annual
frequency of freeze-thaw cycles on the rock surface, as well as the degree of moisture saturation and the ultimate strength of the rocks.

Thus, the periodic freezing and thawing of water in crevices of rocks and ground materials is recognized as an important factor of mechanical (frosty) weathering [26].

2. Object and research methods

Consider the process of one-dimensional freezing of a half-plane with an initial temperature $T_0$ under the action of convective heat exchange at the boundary with the alternating temperature of the medium of the form:

$$ T = T_m + A \sin(\omega t + \varphi) $$

A mathematical model of the process of heat and mass transfer in the surface layer of an array consists of one-dimensional heat conduction and moisture diffusion equations with regard to its phase transformations [27].

For moisture, the boundary condition on the surface corresponds to the condition of conservatism of the system; diffusion flux is zero. The initial uniform moisture content is 0.87 of the maximum moisture content of 0.19.

In (figure 1) showed the result of the calculation of ice content when exposed to the alternating temperature of the medium with the parameters $\omega = 2\pi / t_{\text{per}}$ where the period $t_{\text{per}}$ is 12 hours; The average temperature $T_m$ is determined by the annual trend $A$ - the amplitude of temperature fluctuations in the medium is taken $A = 2^\circ\text{C}$. The estimated time of the freezing process is 200 hours.

A characteristic feature is the appearance of ice content in the surface layers of the rock exceeding the maximum moisture content of the material. As a result of the action of alternating temperatures, situations are possible when the local moisture content $w_w$ and the ice formed $w_i$ is comparable to the pore volume ($V_{\text{pore}}$) and condition (2) is fulfilled. In this case, the growing ice begins to have a mechanical effect on the surrounding rock.

$$ L = (\rho_i \cdot (w_w + 1.1 \cdot w_i) / \rho_w - V_{\text{pore}} \cdot 0.91) \geq 0. $$

![Figure 1. Distribution of ice content by depth (1); maximum moisture content (2); initial moisture content (3).]
Here \( \rho_s \) and \( \rho_w \) are the densities of the rock and water, respectively. Let us assume that the main causes of frost weathering are the redistribution of moisture, its accumulation and freezing in the surface layer, which in conditions of limited pore space can lead to the occurrence of significant destructive stresses.

To determine the mechanical stress caused by the growth of ice inclusions, we use an approach based on the introduction of structural elements (ice inclusions), thickness \( b \) and length \( 2a \), with orientation angle \( \beta \) to the horizontal axis \( x \) of the main coordinate system. We assume that the stress field around the inclusions is determined on the basis of the fundamental solutions of the method of discontinuous displacements [28].

Then the solution of the problem of determining the stress-strain state in a half-plane can be represented as a superposition of two solutions: - the problem of the stress-strain state in an infinite plate with distributed inclusions. Calculation of the stresses caused by them on the boundary elements representing the contour of the surface of the half-plane; - tasks with fictitious boundary conditions equal to negative values of stresses on the surface contour elements.

As a result, the sum of two solutions satisfies the necessary boundary conditions — it ensures the absence of stresses on the half-plane contour. For a two-dimensional ensemble of ice inclusions, the minimization of the elastic energy of the ensemble will be defined as a criterion for choosing their preferred orientation. The starting point is the generation of random uniform angular orientation in the range \((0-360°)\) for the elements of the ensemble of inclusions.

3. Results and discussion
The procedure for minimizing the total elastic energy of an ensemble of inclusions is performed by element-wise variation of the orientation angle. The control results of the minimization procedure are presented (figure 2).

![Figure 2](image)

**Figure 2.** The result of the procedure for minimizing the elastic energy of an ensemble of inclusions of 400 elements.

The results of the evolution of the orientation of the initially uniformly oriented system of inclusions presents (figure 3). Depending on the boundary conditions of the elastic problem, their other equilibrium configurations are possible.
Depending on the frequency of alternating temperature effects, areas of high ice content can form both near the surface and at some distance in the depths of rocks.

4. Conclusions
The simulation results determined that the influence of alternating temperatures on the surface of the thawing massif leads to the formation of preferably one, but rather powerful zone of increased ice content at the boundary with the frozen part of the massif. Schematically, these processes can be associated with the spring and autumn-winter seasons, respectively. It should be noted that the process of accumulation of spring ice is more intense.

In the first approximation, the volume of weathering can be considered proportional to the depth of penetration of alternating temperature oscillations. Detection of spatially ordered structures of ice inclusions will make it possible to estimate the size of areas of partial or complete disintegration of the rocks.

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