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Manifestations of Acoustic Emission in Frozen Soils with Simultaneous Influence of Variable Mechanical and Thermal Effects on Them

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The subject of the research is to establish the fundamental laws of acoustic emission in frozen soils, which allow to create ways to control (monitor) their stability under the influence of variable temperature fields and quasistatic mechanical stress from engineering objects located on these grounds for various purposes. The applied importance of such methods is to increase the speed and reduce the complexity of engineering geological surveys in the northern regions of Russia, carried out with the aim of predicting the loss of stability of the bases of buildings and structures to ensure their safe operation. The study was performed on the original instrumental complex. Its description and characteristics are given. With the use of this complex, thermoacoustic emission effects arising from the repeated alternation of freezing and thawing cycles of the soil during the development of its deformed state, starting from the normal compaction phase and up to the final stage of destruction (the bulging phase), have been studied. It is shown that on the basis of such informative parameters as thermally stimulated activity and duration of acoustic emission pulses, an indicator can be obtained that quantitatively characterizes the stages of the stress-strain state of soils. An experimental dependence of the field of values of this indicator as a function of the mechanical stress and the fractional composition of the test soil is given. The qualitative convergence of this dependence with the classical soil deformation diagram obtained by N.M.Hersevanov is shown, where the stages of compaction, loss of stability (shifts) and destruction are highlighted. Possible physical mechanisms and features of the formation of an acoustic emission response at each of these stages are considered and substantiated. It is noted that the approaches to receiving, processing and interpreting acoustic emission measurement information, which are grounded within the framework of the study, allow to control and monitoring of the carrying capacity and stress-strain state of soils directly in the field.

Key words: frozen and thawed soils; stress bearing capacity; stress state; thermomechanical stressing; acoustic emission; regularities; experiment

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Introduction. The active development of mineral deposits, the intensification of industrial and civil construction in the regions of the Far North increase the risks of man-made disasters associated with the loss of stability of the underground foundations of engineering facilities used for various purposes. In this regard, the problem of increasing the reliability of forecasting the state of these grounds is relevant. To solve this problem, it is necessary to develop new and improve known geocontrol methods that provide the information necessary to manage the risks of the occurrence of relevant anthropogenic threats and to justify effective measures to prevent them.

Traditional approaches [12, 14] to the assessment of the bearing capacity of soil foundations imply the performance of their penetration tests with indenters (piles, punches, etc.) of various designs and (or) soil sampling and their subsequent testing under laboratory conditions. Methods are also known for the in-situ determination of the physicomechanical properties of a soil massif on the basis of shear or collapse of the pillars, as well as using tests using the methods of unstressing and compression. Such approaches to obtaining measurement information are quite informative, however, they are laborious and limitedly applicable for performing long-term observations in the monitoring mode.

Among geophysical methods [3, 5, 6, 11, 13] for monitoring the state of the soil acoustic (seismic, ultrasonic sounding and logging, etc.) and electrometric (geo-radiolocation, electrical profiling, vertical electrical sounding, etc.) are the most common methods. They allow producing control in the monitoring mode; however, they differ in complexity and ambiguity in interpreting the information received and allow only indirectly to judge the condition of soils, their deformation characteristics and carrying capacity. In addition, the implementation of studies of known geophysical methods is time consuming, involves the use of expensive equipment and highly specialized software products that need high-performance computers. This, in turn, creates economic constraints to the use of traditional geophysical methods for assessing the state of soils.

All the above mentioned predetermines the importance of attracting for such an assessment of new cost-effective and innovative methods of geocontrol. One of them is the method of thermally stimulated acoustic emission (TSAE) [14], which has already established itself as an effective tool for studying structural changes, grain size [15], strength properties and stress-strain state of rock and semi-rock rocks [9, 10, 17] and also to control the frost weathering of coals [7, 8]. However, there are only a few attempts to use this method to assess the condition of soils. In particular, the applicability of the TSAE method for studying the dynamics of the deformed state of thawed soils under mechanical stress was experimentally confirmed in [16]. The features of the nature of acoustic emission during freezing and thawing of soils as a function of the relative content of clay and sand particles in them are established. However, studies presented in [16] were carried out on soils with a fairly uniform grain (fraction 0.1-0.25 mm) and each measurement was performed on a fresh sample. This does not allow us to speak about the study of the specific features of the manifestation of thermoacoustic emission effects under repeated mechanical and thermal stressing and unstressing of the same volume of soil with different grain sizes, although such conditions are typical for real soil grounds.

This paper is devoted to experimental studies of the relationship between the dynamics of the carrying capacity of frozen soils with substantially inhomogeneous grain size, subjected to repeated alternating thermomechanical stressing, and parameters of acoustic emission stimulated by this stressing.

Experiments staging. The object of research was the sample of sand-clay mixture from clay of the Chkalovsky field of the Leningrad district (30 % of the dry weight of the sample), alluvial mine sand (70 % of the dry weight of the sample) and water – 20-30 % of the dry mass. The experiments were carried out on three types of weights, differing in the fractional composition of sandy filler: 0.1-0.2 mm (fine-grained), 0.5-1.0 mm (medium-grained); 0.8-2.0 mm (coarse-grained). The experiments were carried out in a laboratory setup (Fig.1).

In more detail the design of the device for thermomechanical stressing of soils is shown in Fig.2.

After mixing with a mixer ensuring uniformity, the sample of soil 1 was placed in a metal flask 2, the upper part of which was sealed by a piston 3 with sealing rings in the lower part. The mechanical action of the lever-mechanical press (not shown in Fig.2) through the plate 4 was transferred to the dynamometer 5 and then through the piston to the soil hitch. When the stress reached a given value, the plate 4 was fixed on the threaded rods 6 with the help of lock nuts 7. This made it possible to maintain the stress created on the ground after removing the device from under the press. Further, the rods 12 located in the central part of the flask were put on the heating elements 8 in the form of conductive coils (not shown in Fig.2, *b*). The A-Line 32D acoustic emission system, via a PAEF-014 preamplifier, connected a GT-2009 piezoelectric transducer located at the bottom of the flask, receiving acoustic emission signals formed in the ground through a duralumin waveguide 10.

For frost impact on the ground, the device was placed in the climate chamber SE 20-45. The transition of temperatures from negative to positive and vice versa, as well as the establishment of the heat flow delivered to the ground, was achieved by adjustment with laboratory transformer that is

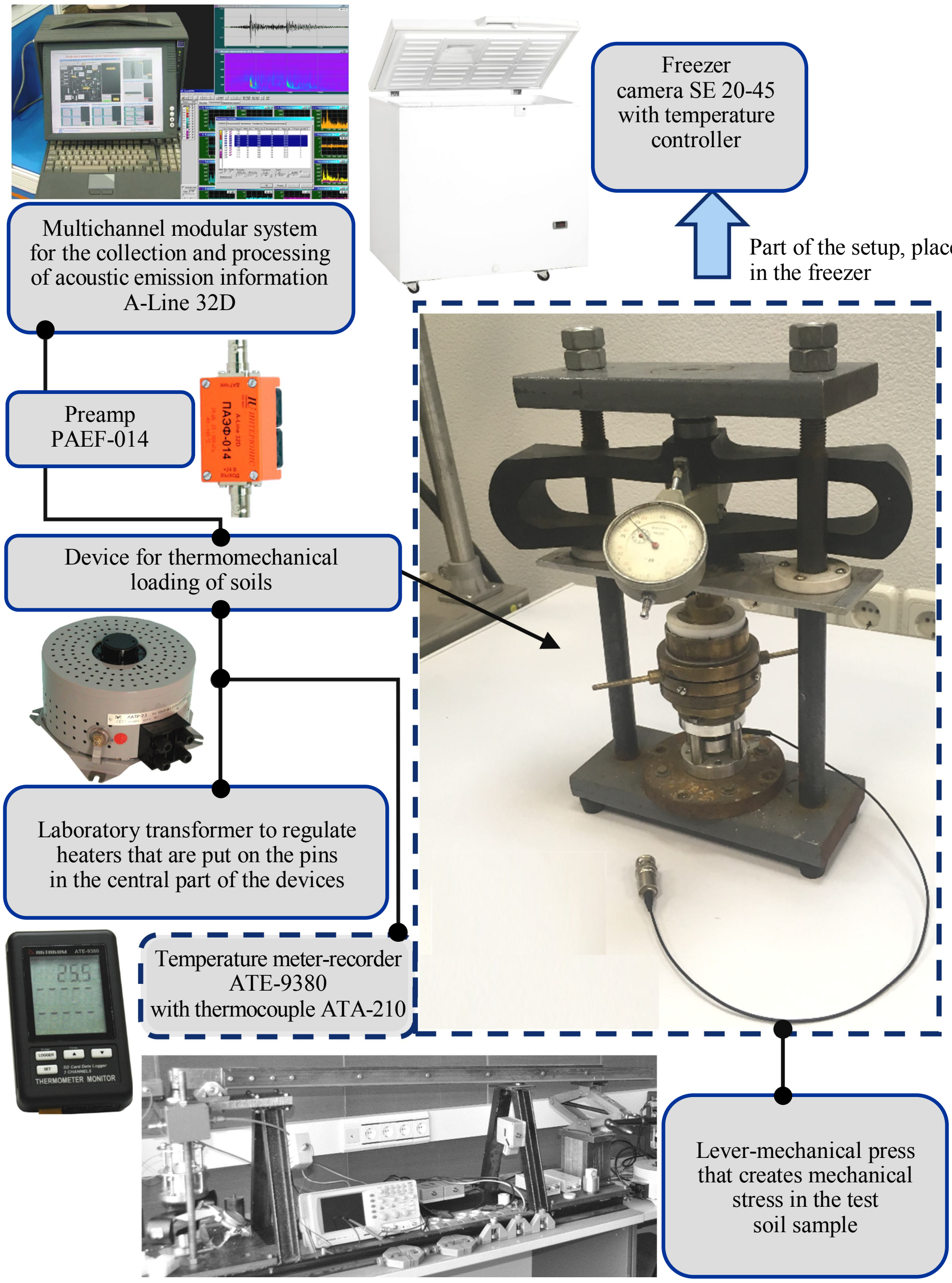

Fig.1. Block diagram of the laboratory setup

applied to the heating elements of the electric voltage. The temperature control during the experiment was monitored using an ATE-9380 temperature meter-recorder with an ATA-210 thermocouple installed in the upper part of the flask. ATE-9380 was once placed outside the freezer.

Thermal stressing was carried out by rapid heating of the metal clamp 11 placed in the center of the flask (Fig.2) to a temperature of ≈ 95 °C. According to the calculations, the heat flux created this way warmed up the soil sample at an average rate of 4-6 °C/min. A typical example of the modes of thermomechanical stressing of samples used in experiments is shown in Fig.3. Due to the long duration of each of the experiments (up to ≈ 18-20 h), it was required to conduct it in several stages. Between them, soil samples, with the recording equipment turned off, were left in the flask under the influence of negative temperatures and with the same mechanical stress that acted on the sample at the time of the end of the next stage. This did not lead to the loss of useful information,

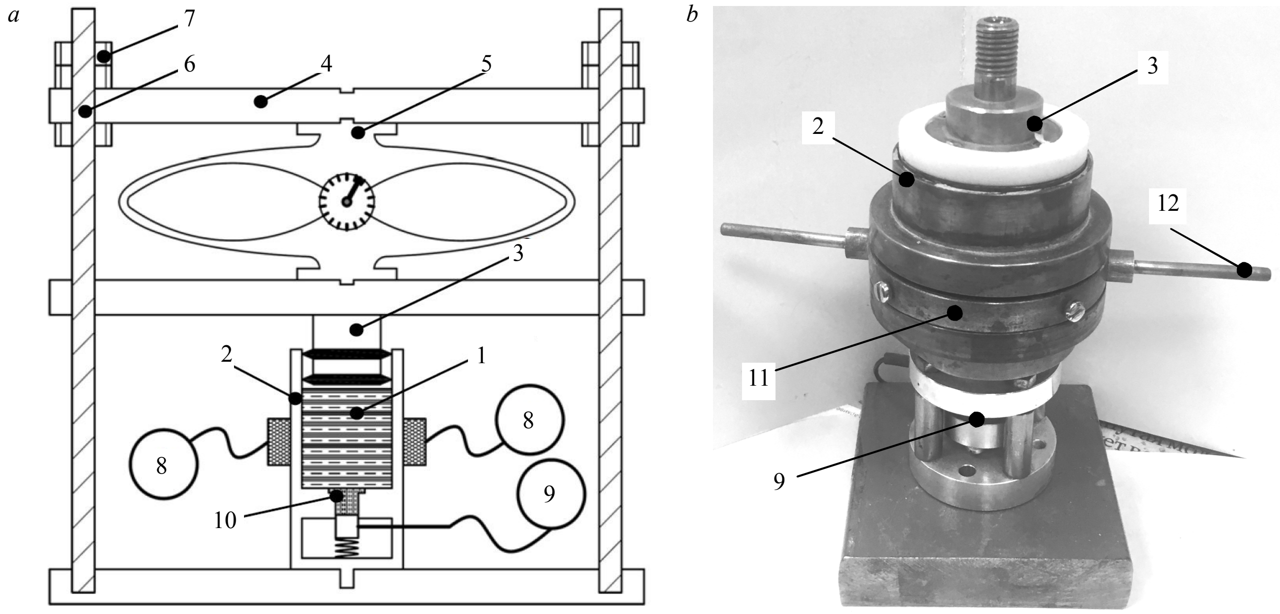

Fig.2. The design of the device for thermomechanical loading of soils (*a*) and the appearance of the test flask (*b*)

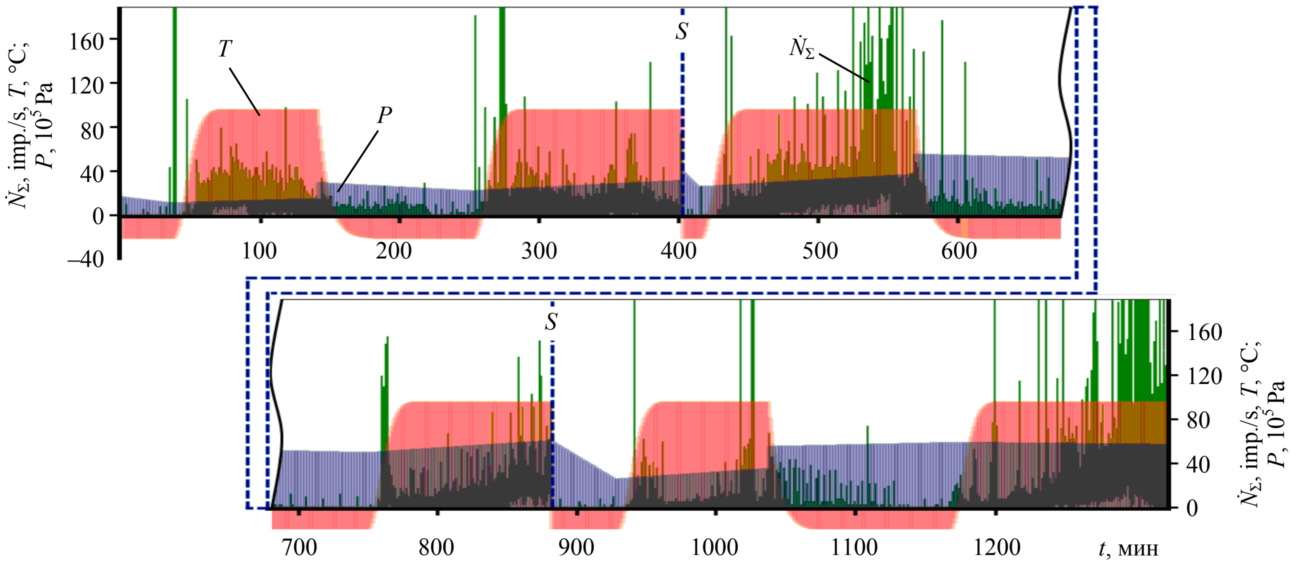

Fig.3. The characteristic form of the primary measurement information on the example of the time dependence $\dot{N}_\Sigma$ in the function on temperature T and mechanical load P of the soil sample with a sandy filler fraction of 0.8-2.0 mm

since the acoustic emission response reflecting the state of the soil is formed either during the redistribution of the mechanical stresses acting in the soil, or during the heating and inertia stages for a limited time after its termination. In Figure 3, the junctions of individual acoustograms obtained during successive stages of recording, data on the same soil sample, are marked with the symbol *S*.

Primary measurement information and processing methods. Activity changes $\dot{N}_\Sigma$ TSAE in time t since the beginning of the experiment under the influence of the dynamics of the mechanical stress acting on the sample P and temperature T are presented in Fig.3. To improve the detailed display, the acoustogram is divided into two parts.

The parameter $\dot{N}_\Sigma$ shown in Fig.3 is traditionally used to estimate the intensity of destructive processes in solids. However, with respect to loose soils, there is no one-to-one relationship between the stage of the deformed state of the sample and the values of the TSAE activity. This is due to the specific features of the organization of structural bonds in the soil material and a very com-

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plex mechanism of interaction between its particles. Thus, in rocky and semi-rocky rocks, the decisive role is played by crystallization bonds, which are not restored after destruction. Therefore, the destroyed crystallization structural bond can no longer become a source of TSAE. Accordingly, the finiteness of the possible number of TSAE events and the clear binding of their realization to the stage of the stress-strain state of the geomaterial greatly simplify the processing and interpretation of the measurement information. This is illustrated in Fig. 4, which shows the typical temperature dependence of the parameter $\dot{N}_\Sigma$ of a sample of granite, which is under constant mechanical stress value 0,8 σ_{ml}.

Consequently, by intensifying the activity of TSAE, as shown in area A (Fig.4), one can judge the onset of avalanche-like defect formation, and the subsequent decrease of $\dot{N}_\Sigma$, caused by the exhaustion of the stock of potential sources of TSAE (preserving the integrity of structural relationships) background values (area B, Fig.4) serves as an indicator of the transition of the geomaterial to the final stage of the stress-strain state, culminating in the imminent dismemberment of the rock by cracks into separate pieces. The latter is accompanied by the formation of single high-amplitude emissions $\dot{N}_\Sigma$ in area B (Fig.4).

In loose soils, along with crystallization bonds, water-colloidal bonds are widespread, which are very plastic and are able to create new compounds immediately after the destruction of old ones. In other words, when stressing the soil material, both processes of destruction and consolidation occur simultaneously in the formation of new structural links (potential sources of TSAE), which significantly complicates the interpretation of the dynamics of the parameter $\dot{N}_\Sigma$. Thus, by itself, this parameter does not allow to determine the current stage of the deformed state of the soil and identify its transition to the state of dangerous development of shear processes and loss of stability. It is clear that for the control and prediction of the latter, the most important is information about the destruction of initially stable structural bonds, which determine the stability of the soil base. At the same time, the acoustic emission response from newly formed temporal and initially unstable bonds is also important, but to a lesser extent, since such bonds are characterized by low strength and, accordingly, affect the bearing capacity of the soil much less. At the same time, such a response contains a large number of acoustic emission events and acts as an interfering component that makes it difficult to isolate elastic pulses, more informative from the point of view of assessing the dynamics of the strength properties of the soil, from the destruction of crystallization bonds.

To calculate the contribution of TSAE pulses from the destruction of various types of structural relationships to the total character, we introduce the parameter D_{imp} – average pulse duration TSAE. Physical sense of D_{imp} – the time during which the structural relationship retains its integrity, being in a stressful state under the impact of external stresses. Accordingly, stable bonds are characterized by larger quantities D_{imp}.

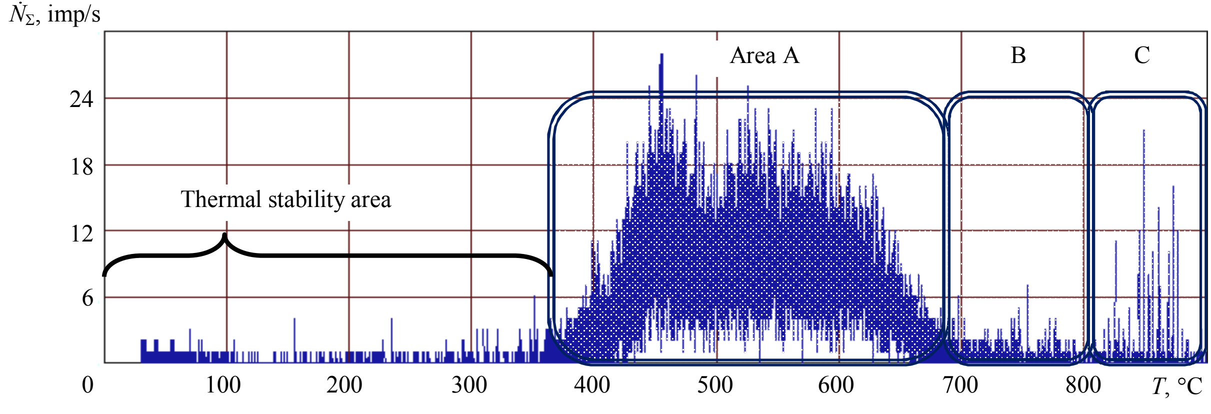

Fig.4. The characteristic dependence of TSAE activity $\dot{N}_\Sigma$ from the temperature T during thermal destruction of a solid, under the simultaneous action of a constant mechanical load

We will separately consider the TSAE at the stage of soil thawing and after its long warming up. At the onset of thermal exposure, acoustic impulses are mainly generated due to acts of destruction of the ice-breed matrix and characterize its strength properties. In its turn, the nature of the TSAE after long-term warming of the soil is an indicator of the intensity of structural changes in the soil, devoid of frozen clay-clay cement. Comparing the performance of TSAE at these stages of soil thawing, it is possible to give a general assessment of the resistance of the geomedia to a given stress and determine how the presence of the ice cage affects the bearing capacity of the soil.

Taking into account the above physical prerequisites, we will use the following three groups of indicators to process the primary measurement information:

1) $M(\dot{N}^{v}_{\Sigma p})$, $M(\dot{N}^{n}_{\Sigma p})$ – TSAE activity values $\dot{N}_{\Sigma}$, averaged over temporary areas corresponding to thermal stressing of fully thawed soil $M(\dot{N}^{v}_{\Sigma p})$and thermal destruction of the ice casing $M(\dot{N}^{n}_{\Sigma p})$with simultaneous exposure to mechanical stress P;

2) D^{v}_{imp} и D^{n}_{imp} values of average duration of acoustic emission pulses, calculated relative to each of the stages of warming up of already thawed soil, which is under the action of mechanical stress P, and each of the stage of thawing of the ice-breed matrix of the sample, respectively;

3) $M(\dot{N}_{\Sigma p})D_{\text{imp}}$ – the weighted average intensity of the destruction of the soil material under the action of local thermal and quasistatic mechanical stress. The values of D_{imp} for weak structural bonds that slightly affect the bearing capacity of the soil are much lower than the value of this parameter for strong bonds. Therefore, the indicator $M(\dot{N}_{\Sigma p})D_{\text{imp}}$ allows to isolate in the general character of the TSAE, destructive events that largely determine the evolution of the bearing capacity of the soil. Thus, the indicator $M(\dot{N}_{\Sigma p})D_{\text{imp}}$ reflects the intensity of destruction of the most stable structural bonds of the soil, determining its carrying capacity as a whole, and allows you to track the evolution and staging of the deformed state of the soil.

We introduce a comprehensive indicator $R^{\text{t.soil}} = (M(\dot{N}^{v}_{\Sigma p})\,D^{v}_{\text{imp}})/(M(\dot{N}^{n}_{\Sigma p})\,D^{n}_{\text{imp}})$.Physical sense of $R^{\text{т.гр}}$ – the ratio of resistance to the thermomechanical effect of the soil material with a fully thawed binder of clay-water cement to the resistance of the same soil in a frozen state to the same stress. In this way, $R^{\text{t.soil}}$ shows the difference in stability of thawed and frozen soil to the action of a given mechanical stress under a certain mode of thawing of the local geomedia area.

Interpretation and discussion of experimental results. Calculation results of $R^{\text{t.soil}}$ for all performed experiments are presented in Fig.5. Each point on it is a summary assessment of data on

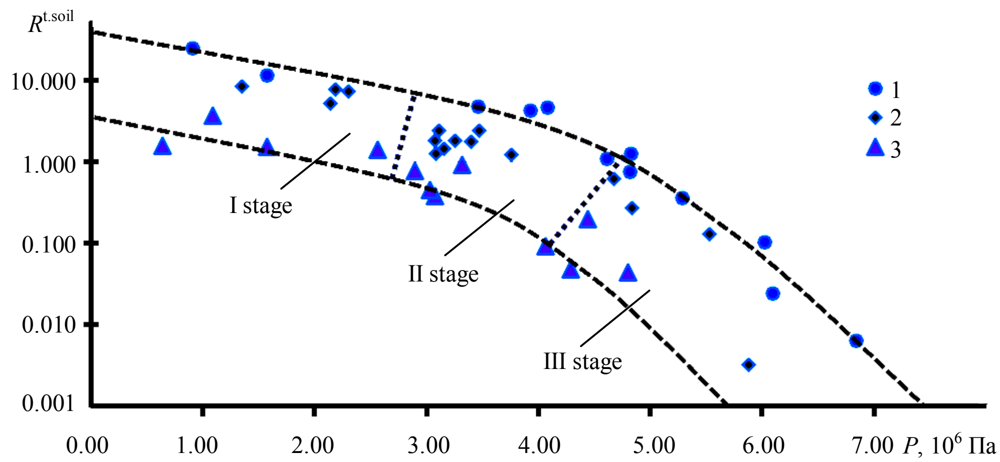

Fig.5. The distribution of the field values of thermoacoustic emission indicator $R^{\text{t.soil}}$ as a function $R^{\text{t.soil}}(P)$ from mechanical loads P at which the corresponding values $R^{\text{t.soil}}$ were obtained

1 – coarse-grained soil; 2 – medium-grained; 3 – fine-grained

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all acoustic emission events that occurred in a sample at a specific stress P over a full cycle of thermal exposure of up to 240 min length. Each such cycle included three stages:

• sample freezing until it is completely freezing, the occurrence of which was judged by reducing the activity of TSAE to background values;

• destruction of the ice-breeding matrix by warming up (controlled by thermometric measurements);

• thermal stressing of thawed soil up to the completion of structural changes in it and stabilization of the deformed state, which was also judged by the decrease in TSAE activity.

The resulting distribution $R^{\text{t.soil}}(P)$ as a function of the average grain size of the test soil is consistent with the known theoretical assumptions, according to which an increase in the granularity of the sand-clay mixture filler, all other conditions being equal, leads to a proportional increase in the carrying capacity. Form of distribution of the cloud of function values $R^{\text{t.soil}}(P)$ also demonstrates the convergence with the view of the classical diagram of the deformed state of the soil. However, the values of P shown in Fig.5 exceed the values of the carrying capacity contained in the reference books, which are similar to the tested ground materials. This is due to the fact that the metal flask, in which the soil weights were placed, played the role of rigid formwork, which significantly impeded the development of shear deformations and the formation of creep phenomena. In other words, from the similarity of functions $R^{\text{t.soil}}(P)$ и $S(P)$ it follows that the mechanisms for reducing the stability of the soil base under the action of a quasi-static external stress are fully preserved, but for the implementation of these mechanisms more powerful stimulation was required.

Thus, the nature of the function $R^{\text{t.soil}}(P)$ is associated with the implementation of the following mechanisms for the formation of acoustic emission response.

At stage I (the phase of normal compaction – deformations mostly caused by the closure of voids between soil particles; there is no risk of loss of stability or it is extremely small), the stresses generated by thermomechanical stressing are not sufficient for the destruction of the soil material. The acoustic emission response is formed due to the melting of the ice cage, fluid migration inside the sample and friction of particles during the closing (reduction) of voids in the soil material. Since the frictional contact between the soil particles is practically not accompanied by acts of destruction, the acoustic emission pulses arising during these contacts have an average duration (D^{v}_{imp}) higher than the pulses formed during the ice matrix cracking (D^{n}_{imp})at the beginning of thermal stressing. This justifies the values observed at this stage $R^{\text{t.soil}}$ up to several dozen units.

At stage II (phase shifts – the ground loses stability, significant shear deformations occur, destruction of the stable structural links remaining up to this point intensifies) local stress concentrators are formed in areas of soil where further compaction by closing the voids is no longer possible. In these areas, the destruction of structural bonds is intensified, including the cracking and overgrinding of clay cement binder. As the destruction of the latter in proportion decreases the carrying capacity of the soil. On the parameters of the TSAE this is reflected in the decrease in the value D_{imp}, which indicates the exhaustion of the stock of strong structural bonds, capable, while maintaining integrity, to withstand thermal and mechanical stresses for a long time. At the same time, the average activity of the formation of new TSAE events $[M(\dot{N}_{\Sigma p})]$ at this stage, can either exceed the value $M(\dot{N}_{\Sigma p})$ at stage I, or remain at the same level, or even be slightly lower. This is due to the fact that in the phase of shifts (according to the classification of prof. N.M.Gersevanov (Fig.6), $M(\dot{N}_{\Sigma p})$ value is primarily af-

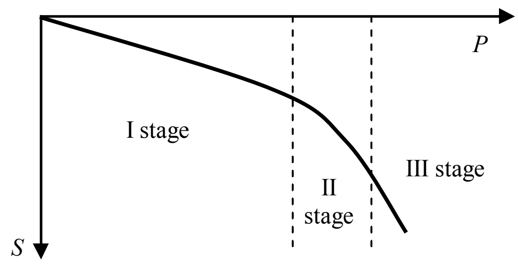

Fig.6. The classical diagram of the deformed state of the soil according to N.M.Hersevanov, showing a general view of the dependence of the increment S of the soil deformation on the load P acting on it

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fected by the destruction of the weak water-colloidal bonds, newly formed directly during the stressing. Their number is large, but the acoustic emission pulses they generate quickly decay. Therefore, if the voltage concentrators were formed in a soil sample at a distance from the receiving transducer, their influence on the general character of the TSAE will be insignificant. In this case, the TSAE will be formed mainly due to the high-energy initially strong bonds, the number of which decreases as the stressing.

Stage III (soil swelling phase – destruction of the soil foundation; if the soil does not emerge from the stress zone due to shear or sticking out, intensive crushing of individual soil particles occurs) is characterized by the ultimate compression of the entire stressed soil volume. The level of TSAE at the thawing stage remains the same, since the strength of the liquid frozen in the ground does not depend on the degree of its deformation. However, at the stage of warming up of completely thawed ground material, which passed to the III stage, the values D_{imp}, $M(\dot{N}_{\Sigma p})$ are at the minimum. This indicates the exhaustion of the possibility of further compression of the mineral frame and depletion of the potential sources of TSAE, namely, the structural links that have preserved the integrity. Upon further stressing, the individual soil particles are crushed, which leads to an avalanche increase in $M(\dot{N}_{\Sigma p})$, but the values of D_{imp} remain low, since each individual crushing event proceeds fairly quickly.

The length of the stages of the deformed state and the distribution of the values of the function $R^{\text{t.soil}}(P)$ directly depend on the strength properties of the soil (see Fig.5). For fine-grained ground weights with initially lower carrying capacity $R^{\text{t.soil}}$ values are significantly lower than that of medium and coarse-grained soil samples. Coarse ground also has a drop in function of $R^{\text{t.soil}}(P)$ smoother than medium grained. For the latter, in its turn, the envelope function of $R^{\text{t.soil}}(P)$ is more gentle in comparison with fine-grained soil.

Conclusion. An experimental study of acoustic emission effects in frozen and thawed flooded soils of different grain sizes with their simultaneous cyclic thermal and mechanical stressing, performed with both constant and increasing or decreasing from cycle to cycle maximum stress, was carried out. The nature of thermo-mutated acoustic emission was studied under repeated mechanical stressing of the same samples. This mode corresponds to the conditions for carrying out full-scale monitoring measurements on the same area of cyclically thawed soil base, in which fatigue phenomena from previously performed influences often distort results of monitoring.

Based on the established patterns of the TSAE nature, a numerical indicator $R^{\text{t.soil}}$ has been developed and substantiated, allowing to judge about the deformed state of the soil with a substantially non-uniform grain. Methodical approaches to obtaining, processing and interpreting measurement information that are substantiated in their work make it possible to control the carrying capacity and deformation state of soils in the monitoring mode directly in the field.

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