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ACOUSTIC EMISSION PATTERNS AS GUIDES TO UNFROZEN WATER IN FROZEN SOILS

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Thermally induced acoustic emission responses of soil samples with different moisture contents to freezing and subsequent local thawing show patterns which can serve as guides to detect and locate zones of unfrozen water in frozen soils. In addition to detection and mapping of thawing zones, theromacoustic emission data can be used to estimate the amount of unfrozen water they contain.

Thermally induced acoustic emission, frozen soil, fluid dynamic processes, unfrozen water

INTRODUCTION

It is impossible to ensure the stability of engineering structures built and maintained in permafrost or in artificially frozen wet ground without reliable knowledge of freezing degree in foundation soils [*Khrustalev et al., 2000*]. Frozen and unfrozen zones are detectable by various geophyiscal methods [*Zykov, 2007*], including source-controlled acoustic emission (AE) measurements of compression and shear wave velocities at high-frequency seismic, sonic, or ultrasonic bandwidths [*Tyutyunik, 1994; Voronkov, 2009; Skvortsov et al., 2011*].

Acoustic wave propagation in frozen ground can be recorded from the surface by reflection and refraction methods or by crosswell logging with regard to specific local conditions and objectives. Such surveys provide information on depths to permafrost because elastic waves travel at different velocities in frozen and unfrozen water-saturated rocks [*Rogers and Morack, 1978; Sellman, 1983; Frolov, 1998*]. However, this information can be ambiguous for wet sand and clay, because the velocities of acoustic waves depend on grain size, temperature, and salinity of soils [*Skvortsov et al., 2014*]. Long-term continuous monitoring of permafrost consumes much time and resources, while it is problematic to ensure stable parameters of measuring systems. Furthermore, the exact radiation pattern (direction) of local acoustic sources has to be known *a priori*, which can be different even within the same site because of composition and structure heterogeneity. As an alternative, quantitative and qualitative assessment of permafrost state is possible with passive observations of acoustic emission (AE).

Among different methods, AE surveys include recording of thermally induced acoustic emission (TAE) of elastic waves from solids exposed to thermal stress associated with heating or cooling and the ensuing irreversible or partly reversible changes in soil structure. The structure changes may result from heterogeneity of thermal loads; difference in thermoelastic properties and thermal expansion of the constituent minerals, and their phase transitions; evaporation or freezing of moisture; explosion of fluid inclusions, or other effects that trigger the formation or growth of defects [*Novikov, 2012*].

The parameters of acoustic emission responding to thermal loads can be used to estimate the structure, properties, and state of soils [*Shkuratnik and Novikov, 2012a,b*]. Although being potentially useful for field monitoring of permafrost, TAE responses of frozen ground have never been investigated so far. The reported experimental study of changes in TAE parameters on soil freezing and thawing, with regard to saturation, substantiate the possibility of such research.

OBJECTS AND EXPERIMENT LAYOUT

Acoustic emission was studied in 1.5–2.0 kg specimens of sand-clay soil, numbered $i = 1...10$, which were wetted before the experiment with $m(0.10 + i{\cdot}0.07)$ of water, where m is the weight of soil in kg. To ensure uniform distribution of moisture in samples, the soil was mixed for 15–20 min with a *Protool MXP 1602 EQ* mixer. The soil-water mixture was placed into a cylindrical metal container, 500 mm high and 400 mm in diameter, and its TAE responses were measured by a group of sensors (transducers) mounted on a rod fixed in the center of the container (Fig. 1). The measuring system was protected from external noise with low-weight bitumen mastic in a fluoroplastic insulation.

The soil-water mixture in the container was frozen to –34 °C in a *SE 10-45* laboratory fridge with the *R404a* cooling agent and was kept at this temperature for at least 90 min; then it was locally heated to 90 °C by a ring conductive heater that encircled the sample in the middle. Thawing progressed as far as the ice-soil matrix became destroyed, and the destruction was detected from temperature change in different parts of the central rod measured by a set of thermistors (not shown in Fig. 1) near each

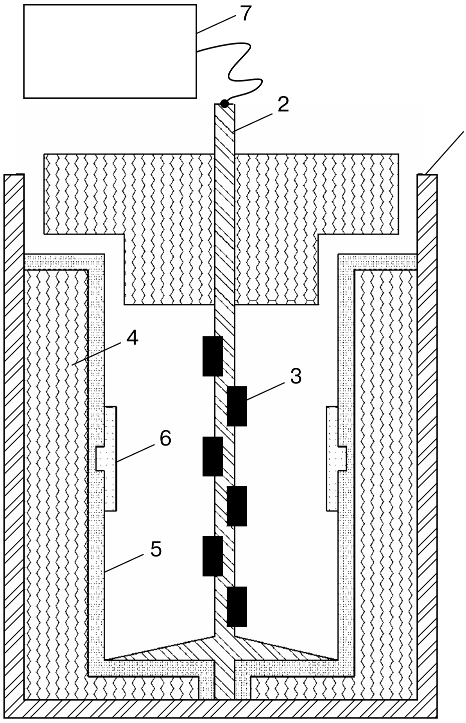

Fig. 1. Laboratory experiment.

1 – cylindrical metal container; 2 – fixed rod; 3 – transducers; 4 – bitumen mastic; 5 – fluoroplastic insulation; 6 – ring heater; 7 – TAE measuring system.

transducer. This method is suitable to detect ultimate failure of the soil matrix but cannot resolve variations in the amount of unfrozen water over the sample.

The AE signals from each transducer, as well as the readings of the thermistors, were recorded and processed by an *A-Line 32D* AE system.

PROCESSING AND INTERPRETATION OF MEASURED TAE RESPONSES

The experiment results (Fig. 2) were processed using the parameter of average TAE activity $\left(\mathrm{M}\left(\dot{N}_{\Sigma n}\right)\right)$ for a selected time span, where *n* is the span number. In all cases, $\dot{N}_{\Sigma}$ is much lower for an existing ice-soil matrix (domain A: $\mathrm{M}\left(\dot{N}_{\Sigma}\right) =$ $= 0.038$ pulses per second (Fig. 2, *a*); 0.055 pulse/s (Fig. 2, *b*); 0.049 pulse/s (Fig. 2, *c*)) than for its formation by freezing (domain B: $\mathrm{M}\left(\dot{N}_{\Sigma}\right) = 4.1$ pulse/s (Fig. 2, *a*); 57.4 pulse/s (Fig. 2, *b*); 141.7 pulse/s (Fig. 2, *c*)) or destruction by thawing (domain C: $\mathrm{M}\left(\dot{N}_{\Sigma}\right) = 5.6$ pulse/s (Fig. 2, *a*); 69.6 pulse/s (Fig. 2, *b*); 159.4 pulse/s (Fig. 2, *c*)).

The $\dot{N}_{\Sigma}$ value varies with cooling or warming depending on water content and approaches the initial level when the ice-soil matrix becomes destroyed (Fig. 2). The variations result from fluid dynamic processes in soil, e.g., gravity-driven redistribution (cross-flow) of fluid inside the solid.

Thus, the more active the freezing-thawing processes the higher the AE activity depending on the amount of water involved. The percentage of fluid converted to solid by the time of measurement can be estimated as a ratio of average activity $\mathrm{M}\left(\dot{N}_{\Sigma 0}\right)$ recorded in a sample with at least 80 % of unfrozen water to the value $\mathrm{M}\left(\dot{N}_{\Sigma i}\right)$ measured during thawing or freezing. $\dot{N}_{\Sigma}$ is slightly higher during thawing as the ice-soil matrix becomes denser while the losses of AE signals are smaller than during freezing when the acoustic transmission channels are worse developed.

POSSIBLE PRACTICAL USES

The TAE patterns of freezing and thawing soils can be diagnostic of the amount and location of unfrozen water (Fig. 3). For this application, TAE responses of the soil block (1 in Fig. 3) are recorded in cores from boreholes (2 and 3 in Fig. 3) drilled for freezing or piling. TAE measurements are performed parallel to the standard weight measurements of water content C_i in cores exposed to thawing [*Soils, 1984*]. The specific TAE activity $\mathrm{M}\left(\dot{N}_{\Sigma}^{\mathrm{sp}}\right)$ is estimated as an average number of signals received from each cubic cm of the sample for a certain discrete time span. The maximum spacing of transducers is chosen specially for each soil type proceeding from the maximum distance at which AE recording remains effective.

Then the $C_i\left[\mathrm{M}\left(\dot{N}_{\Sigma}^{\mathrm{sp}}\right)\right]$ and total water content in cores $C_{\Sigma} = \sum_i C_i$ are plotted as a function of depth *h* separately for each borehole. At the next step, transducers spaced at 0.8–1.0 m are placed into holes or are mounted on piles in the same way as on the rod of the laboratory system (Fig. 1). Each transducer records TAE responses to fluid dynamic processes in soils. The TAE activity $\mathrm{M}\left(\dot{N}_{\Sigma}^{\mathrm{sp}}\right)$ is averaged over successive periods of time *n* of commensurate lengths (about 30 min) chosen beyond the time of construction and maintenance activities which cause strong soil vibration (for example in the night). Thus obtained data are used to calculate depth dependences of the $\mathrm{M}\left(\dot{N}_{\Sigma n}^{\mathrm{sp}}\right) / \mathrm{M}\left(\dot{N}_{\Sigma 0}^{\mathrm{sp}}\right)$ ratio, which look like curves I and II in Fig. 3. $\mathrm{M}\left(\dot{N}_{\Sigma 0}^{\mathrm{sp}}\right)$ is meant as the AE activity in a core with at least 80 % of unfrozen water from the same site where the respective $\mathrm{M}\left(\dot{N}_{\Sigma n}^{\mathrm{sp}}\right)$ value was recorded. The presence and location of the unfrozen

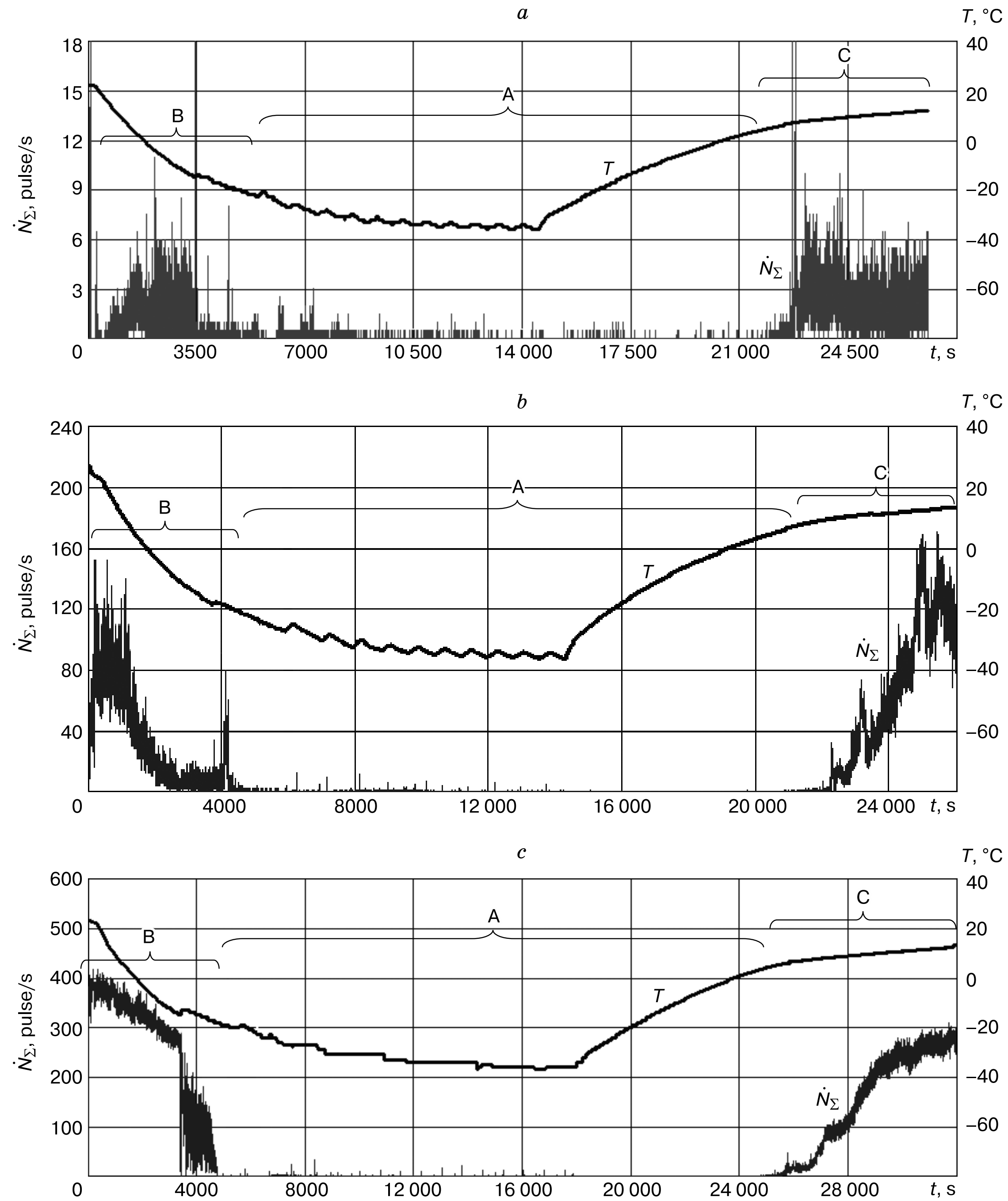

Fig. 2. Typical empirical relationships of AE activity $\dot{N}_\Sigma$ and temperature T in the middle of soil samples with water contents 24 % (*a*), 52 % (*b*), and 80 % (*c*) exposed to complete freezing (domain A), cooling (domain B), and thawing (domain C).

zone in frozen ground is marked by $\mathrm{M}\left(\dot{N}_{\Sigma n}^{\mathrm{sp}}\right)$ exceeding (1/3) $\mathrm{M}\left(\dot{N}_{\Sigma 0}^{\mathrm{sp}}\right)$, while $\mathrm{M}\left(\dot{N}_{\Sigma n}^{\mathrm{sp}}\right)$ below this threshold indicates the stability of soil freezing. The unfrozen zones are mapped knowing the location of transducers with the respective readings.

The amount of unfrozen water is estimated as a dot product of h dependences of the average acoustic emission ratio and the total water content $C_\Sigma(h)\cdot\left[\mathrm{M}\left(\dot{N}_{\Sigma n}^{\mathrm{sp}}\right)\big/\mathrm{M}\left(\dot{N}_{\Sigma 0}^{\mathrm{sp}}\right)\right](h)$ obtained at the same depth in the same borehole.

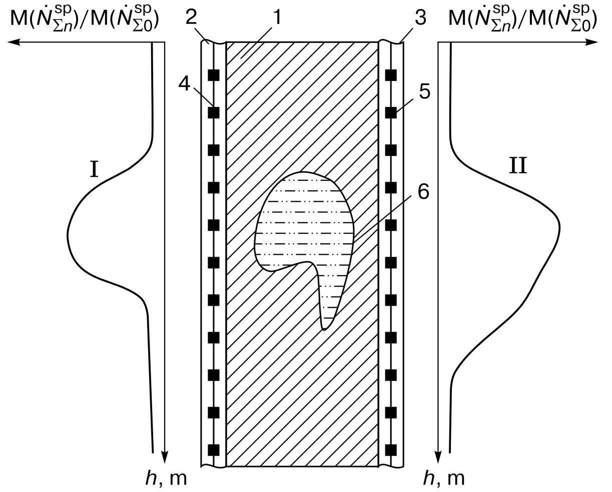

Fig. 3. Method for estimating the amount and location of unfrozen water in frozen soil from TAE responses.

1 – block of soil; 2, 3 – boreholes; 4, 5 – groups of acoustic transducers; 6 – lens of unfrozen water. Curves I and II are depth (h) dependences of the $\mathrm{M}\left(\dot{N}^{\mathrm{sp}}_{\Sigma n}\right)\Big/\mathrm{M}\left(\dot{N}^{\mathrm{sp}}_{\Sigma 0}\right)$ ratio.

Note also that the monitoring can be reduced to passive observations of AE dynamics from the $\mathrm{M}\left(\dot{N}^{\mathrm{sp}}_{\Sigma n}\right)\Big/\mathrm{M}\left(\dot{N}^{\mathrm{sp}}_{\Sigma 0}\right)$ ratio for detection and mapping of unfrozen zones, without coring and core measurements, which are required only for estimating the amount of unfrozen water.

CONCLUSIONS

1. Acoustic emission responses of soils with different water contents to thermal loads of freezing and thawing as a function of freezing degree have been studied with specially designed instruments and methods.

2. The patterns revealed during the studies were used to develop a method for estimating the amount and location of unfrozen water in frozen ground from TAE responses. Continuous AE monitoring of soils can provide precise and reliable detection of unfrozen zones at their inception and allows quantitative estimation of water amount and its dynamics.

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References

Frolov, A.D., 1998. Electric and elastic properties of frozen soil and ice. ONTI PNTC RAN, Pushchino, 515 pp. (in Russian)

Khrustalev, L.N., Medvedev, A.V., Pustovoit, G.P., 2000. Long-term air temperature variations and stability of structures in permafrost. Kriosfera Zemli IV (3), 35–41.

Novikov, E.A., 2012. Thermally induced acoustic emission of rocks and soils: State of the art. Gorn. Inform.-Analit. Bull., No. 5, 394–401.

Rogers, J.C., Morack, J.L., 1978. Geophysical investigations of offshore permafrost at Prudhoe Bay, Alaska. Proc. 3th Intern. Conf. on Permafrost, Edmonton, Canada, vol. 1, pp. 560–566.

Sellman, P.V., 1983. Seismic velocities and subsea permafrost in the Beaufort sea. Proc. 4th Intern. Conf. on Permafrost, Fairbanks, USA, vol. 1, pp. 894–898.

Shkuratnik, V.L., Novikov, E.A., 2012a. Detection of structure defects in rocks from thermally induced acoustic emission, in: Physicochemical and Petrophysical Studies in Geosciences. Proc. 13th Intern. Conf., IGEM RAN, Moscow, pp. 291–294.

Shkuratnik, V.L., Novikov, E.A., 2012b. Correlation of thermally induced acoustic emission and ultimate compression strength in hard rocks. J. Mining Science 48 (4), 629–635.

Skvortsov, A.G., Tsarev, A.M., Sadurtdinov, M.R., 2011. Seismic studies in frozen ground. Kriosfera Zemli XV (4), 96–98.

Skvortsov, A.G., Sadurtdinov, M.R., Tsarev, A.M., 2014. Seismic identification criteria of the frozen state in rocks. Kriosfera Zemli XVIII (2), 83–90.

Soils: Laboratory Determination of Physical Properties, 1984. GOST 5180-84 (Gosstroi SSSR of 24.10.1984, No. 1985). Izd. Standartov, Moscow. (in Russian)

Tyutyunik, P.M., 1994. Geoacoustic Monitoring of Freezing and Filling of Rocks. Nedra, Moscow, 251 pp. (in Russian)

Voronkov, O.K., 2009. Engineering Seismology in Permafrost: Studies of Structure and Properties of Frozen and Unfrozen Soils. VNIIG, St. Petersburg, 401 pp. (in Russian)

Zykov, Yu.D., 2007. Geophysical Surveys in Permafrost. Moscow University Press, Moscow, 272 pp. (in Russian)

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