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GEOCRYOLOGICAL MONITORING AND PREDICTION

CONTROL OF THE TEMPERATURE CONDITION OF A MINE BASE ON PERMAFROST BY AUTOMATED MONITORING

V.V. Neklyudov, S.A. Velikin, A.V. Malyshev

Melnikov Permafrost Institute, SB RAS, Viluj Permafrost Research Station, Chernyshevsky settlement, 4 VNIMS, Mirny Region, Sakha Republic, 678185, Russia; nviva@mail.ru

In order to increase the efficiency of control of permafrost degradation in the bases of large mines established on permafrost, a new approach to monitoring the condition of frozen ground has been suggested. This approach is based on using new automated temperature logger systems. The description of the operating model of a permafrost degradation control system in the ground of an engineering facility base is provided. Control is effected by registering the temperature field. The components of the direct and backfeed loop of this system are defined. It has been demonstrated that using three-dimensional isothermal surfaces of the temperature field of the object base is optimal for detecting the thermal characteristics of a facility.

Mine base, permafrost degradation, isothermal surface, a logger, a control system, a temperature field

INTRODUCTION

Monitoring the temperature as the main characteristic of the phase condition of grounds is the primary link in any system made to control permafrost degradation both in the bases of structures erected in the permafrost zone and in their engineering systems and geological environment [*Kondratyeva and Konovalov, 1989; Gorelik et al., 1997; Kamyshev, 1999; Drozdov et al., 2007; Pavlov, 2008*]. Regarding engineering facilities located in the permafrost zone, progress in development of technical measuring devices allows installation of modern thermal control logger systems in the foundations of the existing mines to control their condition. In addition, the method of providing primary data is changing. Whereas until recently primary information has been presented as a set of simple temperature plots, now 3-dimensional temperature fields and their derivatives are replacing these plots, thus showing the process in its development. These are qualitative changes, which require adequate description in specialized literature.

The scientists of the Viluj Permafrost Research Station (VPRS) have developed a thermal control system, which has been tested in the technological cycle of freezing ground in the bases of Mir and Internatsionalny mines. They have also developed and tested a software program called *Thermic* as part of the permafrost control system for mine bases (as a model), allowing provision of recommendations to change the semi-automated and automated modes of freezing pipes.

THE PERMAFROST CONTROL SYSTEM

The system for control of the permafrost condition at the foundations of engineering structures established in the permafrost zone is understood as a classical automated control system (ACS) (see, for example, [*Galperin, 2004*]), the main components of which in this case are: 1) a thermal control measurement system; 2) a freezing station; 3) a system for control of the permafrost condition. Each of these subsystems has its own control add-in.

With direct participation of the researchers of the Melnikov Permafrost Institute, SB RAS, operation of a new digital thermometric system started at Mir mine, allowing on-line registration of the temperature field at the rate required under current engineering and geocryological conditions, for example, in case of ground waters penetrating the mine foundation. The system is a borehole network, containing logger strings located in a mine foundation. The network has an interface (bus) with a central control unit, etc. Attached to this system is an Act for Testing Permafrost Temperature Control Loggers ("Testing Act"), provided by the VPRS of MPI, SB RAS (Yakutsk, 2011), and a Certificate of Approval the Type of Manufacture for a Measurement Instrument has been obtained by the VPRS of MPI, SB RAS.

The temperature control system (TCS) is a hierarchic four-level system. The first level consists of multiple-zone immersion probes, each of which has up to 16 temperature converters, spaced at the distance of 1 m. The second level of the system consists of electronic modules designed for receiving informa-

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tion from the probes. Up to 7 probes may be connected with one module. Data exchange is conducted by the 1-Wire bus, effected on the basis of screened cable less than 100 m long. The third level includes electronic modules acting as interface converters and designed for receiving data from the second-level electronic modules and for data exchange with a computer by the USB serial interface lines. The maximum number of the second-level modules than can be connected with WAD-LAN/RS232/USB/RS485-BUS is 10.

The use of freezing stations in underground construction is well-spread and widely described, for example, in [*Trupak, 1974*]. Circulation of a cooling agent ensures freezing of the ground to a certain critical value, equal to the difference of temperatures (ΔT) between the receiving ground and the cooling agent. As this difference reaches zero, the station is switched to the standby mode (with only the ground heat flow absorbed). Special efficiency issues of using a freezing station in the Mir mine have been considered in [*Lobanov et al., 2005*].

An automated permafrost control system is the least developed element. Until recently, in most mines located in the permafrost zone of RF, control of the freezing stations has been exercised via a system of written recommendations, authorized by a signature of the person responsible for the station's operation mode.

The open-architecture software complex *Thermic* allows automated control of the permafrost condition by timely change of the operation modes of the freezing pipes in order to maintain the optimal mode (by the criteria set) of the carrying capacity of the grounds in the base of an engineering facility. Here direct connection (as an element of ACS) is effected by the borehole network temperature data coming to the input of the software complex to be processed. Feedback is exercised via a channel with the freezing station, along which commands are issued to change its operation mode.

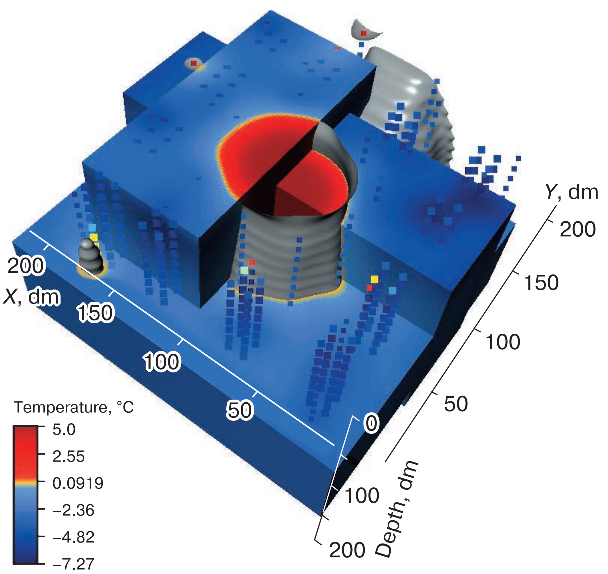

Fig. 1. The temperature field in the ground of the skip shaft with a ventilation duct of Mir mine.

The grey color is the zero isothermal surface; columns – foundation piles.

ON-LINE TEMPERATURE MONITORING

The geocryological stability of grounds in the base of engineering structures is understood as primarily maintaining the carrying capacity of the foundation piles [*Rastegayev, 2001*]. However, in order to assess it, it is necessary to know distribution of ground temperatures along each pile of the foundation's pile field, as well as their water flooding and salinity, the physical characteristics of grounds, etc. As the network of the thermometric boreholes of the mine is scarce and does not coincide with the position of the carrying piles, there arises a problem of precise determination of temperatures along these piles (the errors of their determination may lead to the errors of calculating the carrying capacity). It is difficult to solve this problem in an analytical way; therefore the *Thermic* software program was used to plot the temperature fields of general axial symmetry on the basis of interpolation algorithms. With this program, using the measurement data of the thermal control system, 3D temperature fields were obtained as the primary and main element of the total permafrost monitoring. In all the figures shown below, the plotting is made reaching the depth of 20 m. The results are shown for the skip shaft of the Mir mine in Fig. 1–3.

The *Thermic* software program automatically determines the presence of thawed areas both in the entire temperature field of the foundation and along each pile. For each such section, the value of excess of its temperature over the admitted temperature (in accordance with the Permafrost Inspection) is determined, and the nearest freezing pipe is located (Fig. 2). Note that Fig. 2 shows not the precise temperature field but a kind of its interpretation, insignificantly distorting it. This information (the value of the temperature anomaly and the number of the nearest freezing pipe) in all the sections is sent to the control unit of the freezing station to increase the power of these pipes, in order to compensate thawing. The frozen areas of the foundation grounds are found in a similar way; information about the number (name) of the nearest pipe giving the value of the temperature anomaly is also sent to the freezing station control unit to reduce the power of the pipes. The operation time of a freezing station in a new mode may be evaluated considering the reactivity of the freezing impulses, in fact, by the current freezing rate. The freezing

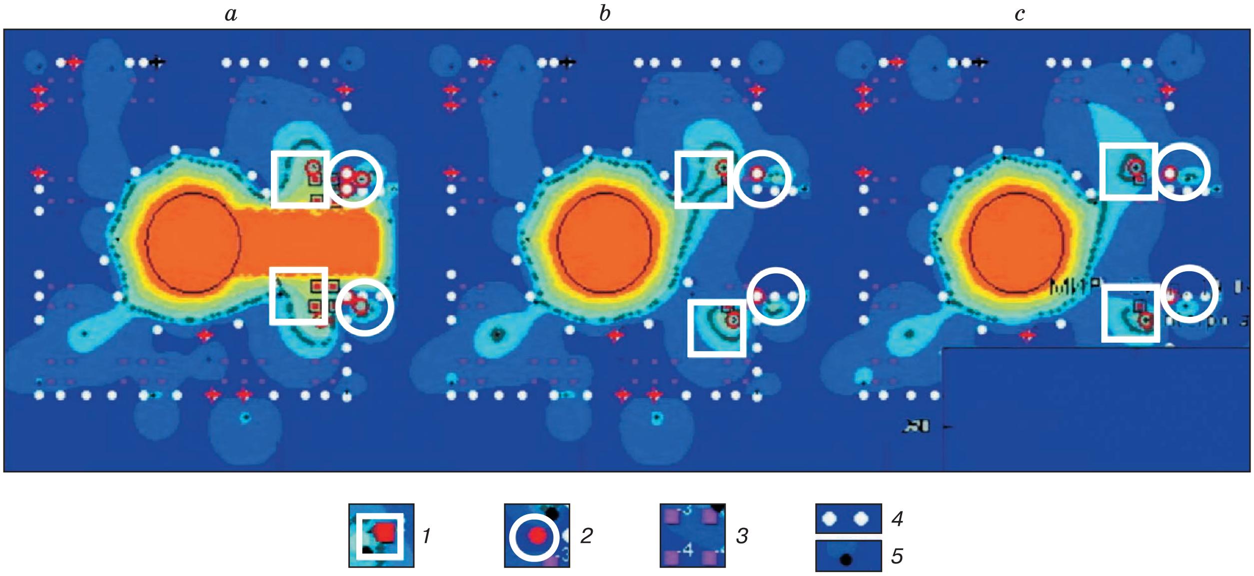

Fig. 2. Examples of automatic identification (*a*–*c*) of thawed piles and of the freezing pipes nearest to them.

1 – piles found in an emergency condition; *2* – modelled nearest freezing pipes in an emergency condition; *3* – the pile field; *4* – the freezing system; *5* – the thermometric system.

rate of the grounds in *Thermic* is determined directly, numerically, as the rate of shifting the zero isotherm for the given period of time (not shown here).

If necessary, the 3D temperature field (considering moisture content, salinity, ground type, and pile parameters) may be recalculated as the carrying ca-

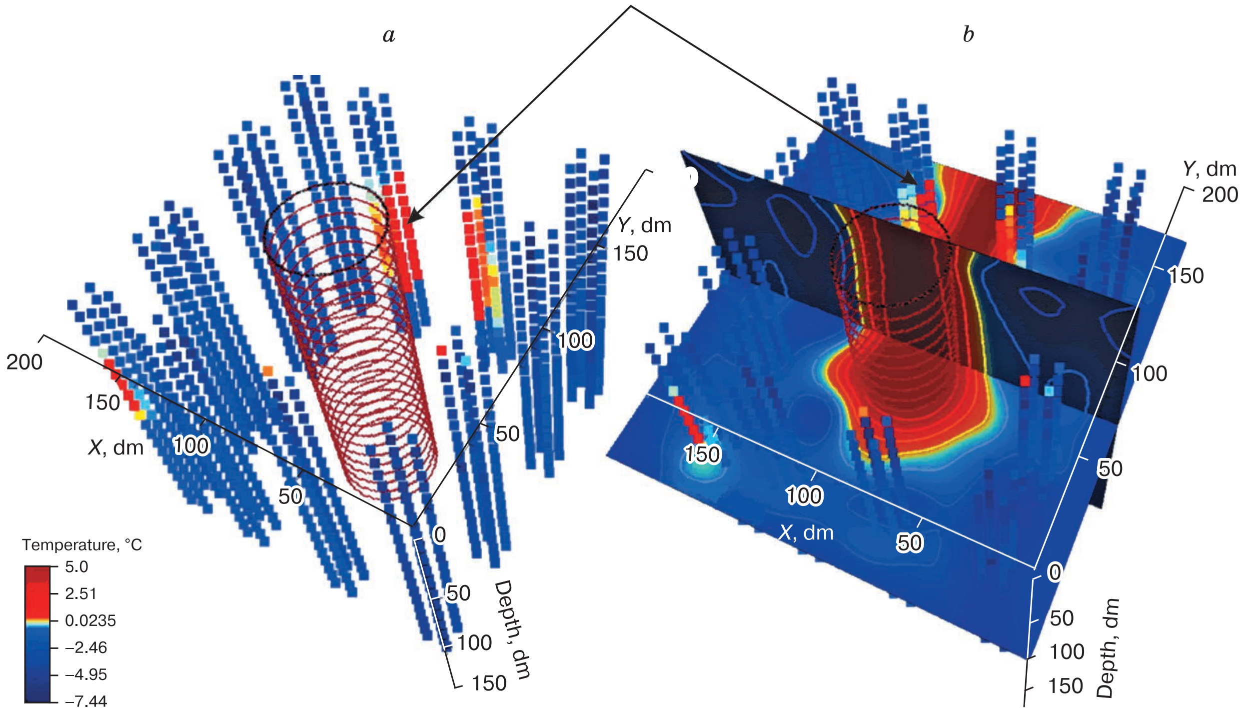

Fig. 3. Temperature piles modelled as far as the depth of the skip shaft of Mir mine (*a*) and of the cross section of its temperature field (*b*).

The arrows stand for abnormally thawed piles of the ventilation duct.

pacity of the pile on the basis of known formulae, in accordance with the regulating documents. The freezing system is switched over when the carrying capacity of the grounds reaches a certain limit, in accordance with the regulatory documents (SNiP). Due to methodological considerations, we used the temperature criterion beyond the reach of SNiP, according to which the temperature distribution along piles is considered as the first approximation to the criterion of the carrying capacity. The temperature range from −2 to 0 °C is considered to be a range of loss of the carrying capacity by the piles. Hereinafter the term "temperature pile" will be understood as a digital temperature counterpart of an actual pile, obtained as the average value for the pile facets from the temperature cube retrieval along the four facets of a pile. For the foundation of Mir mine, Fig. 3 shows comparison between the temperature piles and the cross sections of the foundation's temperature field.

The Internatsionalny mine is shown in cylindrical approximation, without elements like a ventilation pipe (Fig. 4), as the temperature field of the cylindrical thermal source has been studied most thoroughly. Thermal anomalies (from −2 to 0 °C and higher) on temperature piles directly point to the areas which should be paid special attention to in calculating carrying capacities. Similarly, frozen areas of foundation grounds are found, while information about the number of the nearest freezing pipe is sent to the control point of the freezing station, to reduce the power of this pipe.

The *Thermic* software program is oriented on the digital version of the thermal control system, measuring the ground temperatures at random, including variable, rates. For engineering geocryology, this is a technologically innovative type of temperature data, possibly telemetric data, interpreted in the online (or current) mode.

The complex for temperature control of structure foundations allows the following tasks to be solved.

1. The main purpose of the complex is to alarm the geocryological safety system of a company on the presence or emergence of thaws in the ground in the pile field areas directly using thermometric boreholes and bore pits.

2. The hazard of formation of thawing areas equally distanced from thermometric boreholes consists in the fact that they can be developed vertically and are not detected until the impact of the already formed heat source in the foundation ground spreads to the nearest thermometric borehole. Therefore the task of optimal interpolation of the temperature field by the rare data in order to detect hawed areas is always topical.

3. The task of thermal stabilization of foundation ground, considering the reactive character of the freezing impulses [*Porkhayev, 1970*], is viewed as a classical problem of ACS with feedforward by temperature measurements and feedback by the freezing station mode. The variant of its solution is shown above.

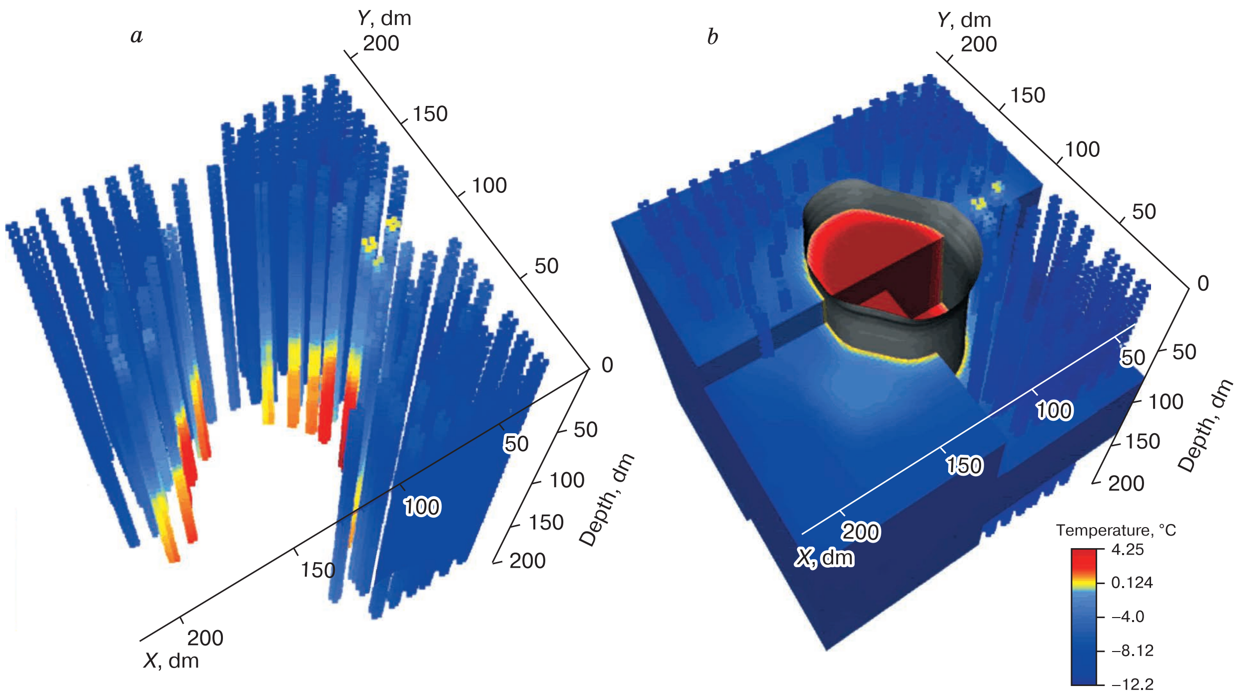

Fig. 4. Temperature piles of Internatsionalny mine (*a*) and the temperature field of its foundation with zero isothermal surface (*b*).

It is to be considered that whereas for earth fill dams a solid ice barrier is required, it is necessary to protect certain concrete structures against excessive freezing at the mine foundations. The latter detail necessitates maintaining the carrying capacities of piles in a relatively narrow range of negative temperatures. In addition, such a task is more complicated due to reactivity of the freezing impulses, the presence of possible saline areas, and significant irregularity of foundation ground freezing (freezing rate).

4. The task of maintaining a regular freezing mode is solved by automated (software) monitoring of the freezing rate.

5. Based on the updatable database of the 3D temperature fields ("the temperature history"), the Thermic complex may do temperature field scans of foundations in random cross sections at different rates of its changing with the time, characterizing the behavior of the so-called stock of cold in the foundation ground. In addition, the behavior of the temperature field is predicted and the current temperatures are compared with its predicted values.

PLOTTING ISOTHERMAL SURFACES

Currently the reports due to the Permafrost Inspection prepared by most mining-and-processing companies in the permafrost zone are presented as simple temperature plots. However, if a pile is in an indeterminate zone of phase transitions, then, in the absence of spatial temperature data, it is difficult to evaluate the probability rate of its geocryological instability, should it become necessary.

Three-dimensional isothermal surfaces (three-dimensional distribution of phase transitions in the foundation volume) in a production process are a relatively new tool, which can offer serious advantages. They provide an overall impression of the specific features of distribution of phase transition fields for the entire foundation volume (Fig. 5) and allow solving problems, for example, those set by the Permafrost Inspection, at a qualitatively new level.

RESULTS

It is reasonable to evaluate the condition of mine foundations in the permafrost zone on the basis of modern thermometric logger systems, allowing random rate of measurements, depending on the current engineering and cryohydrogeological situation in the ground [*Lobanov et al., 2005*]. Using the data obtained, we propose to plot 3D temperature fields and their derivatives (in particular, isothermal surfaces) and their behavior. It is necessary to reveal (using software in an automated mode) thawed areas (from −2 °C and higher) by the temperature piles as areas of loss by the actual piles of their actual carrying capacity. The effectiveness, fastness and reliability (as the human factor is excluded) of permafrost monitoring

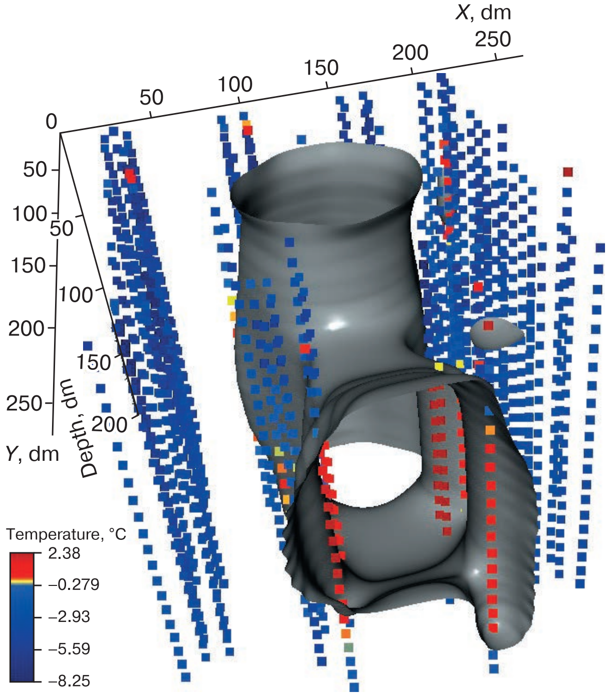

Fig. 5. Temperature piles and the isothermal surface of the grounds of Mir mine foundation (the skip shaft with a ventilation duct).

at the mine foundations may be increased by automated setting of the mode of a freezing station using feedforward and feedback.

The possible weaknesses of the proposed approach, related, in particular, to the large volume of the three-dimensional data, can be easily dealt with by the use of available hardware with standard software installed.

CONCLUSION

The study relates the technical characteristics of a thermal control system and describes a model of a software package for control the permafrost condition in the foundations of Mir and Internatsionalny mines (as a prototype of a specialized ACS, with typical 3D temperature fields and their special areas (temperature piles, cross sections, thawed areas, etc.) shown.

The authors hope that the materials provided will be helpful in developing new approaches to permafrost monitoring at the engineering facilities erected in the permafrost zone.

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