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DETERMINATION OF THE MOMENTS AND RATE OF CHANGE IN THE STRESS STATE OF GROUNDS FROM VARIATION IN INFRARED RADIATION FLUX FROM THE SURFACE

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Results of studies in which measurements of infrared radiation from the surface of geomaterials were used to obtain information on variation in their mechanical state are reported. Physical principals of the approach are briefly described. Instrumentation and a technique are designed to obtain synchronous records of pulsed variations in load on a ground sample subjected to compressive contraction and corresponding variations in the flux from its surface. An algorithm of coprocessing of the records obtained is constructed. It is shown that data of thermal-radiation measurements can be used to advantage to detect moments at which the stress state of grounds changes and to estimate relative magnitudes of these changes.

Time variation of stresses in massifs of grounds and rocks is a characteristic manifestation of the activity of mechanical processes occurring in them. Detection of these variations and determination of their magnitudes can be used to assess the influence of different effects on the state of massifs and to detect and predict the development of hazardous natural and technological processes [1, 2]. Grounds, especially soft, are the most complicated type of geomaterials from the point of view of experimental analysis of their mechanical state [3–5]. Over the last years, considerable attention has been given to the use of different physical methods for geomonitoring [6, 7], mostly as applied to rocks and concrete. The present studies [8, 9] seek to develop and improve the technique of monitoring stress variations in geomaterials, which is also applicable in massifs of grounds. The technique uses the thermodynamic effect of variation in the temperature of a body upon its deformation [10] and the dependence of the infrared (IR) radiation flux from the surface on the temperature of the body [11, 12].

In elastic deformation in the adiabatic regime, the temperature variations ΔT and the first invariant of the stress tensor $\Delta\Pi$ at a point of the medium are connected by the relation [10]

$$\Delta T/T_0 = A_m \Delta\Pi, \tag{1}$$

where T_0 is the initial temperature of the body [K], and the quantity A_m [1/Pa], which is conveniently called the coefficient of thermoelastic-activity coefficient [8], depends on the density and thermal properties of the material.

Adiabaticity, i.e., the absence of heat exchange between a deformable body and the ambient medium and also between different segments of the body, is apparently only approximate under real conditions. However, this approximation is quite adequate if the rate of change in temperature with time is much higher due to the thermoelastic effect than due to heat exchange. Such quasiadiabaticity occurs, for example, in standard regimes of tests of geomaterial samples [8].

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Linearizing the dependence of the IR-radiation flux W on the body temperature on $(\Delta T/T_0) \ll 1$ [11] and using (1), we obtain

$$\Delta W = A_c(\Delta T/T_0) = A_c A_m \Delta\Pi, \tag{2}$$

where the emissivity of the material A_c [W/m^2] [8], which contains the Stefan–Boltzmann constant as a cofactor, depends on the temperature and emissivity of the surface.

Using (1) and (2) and assuming that the measured values of U (in units of the scale of the device) are linear functions of the values of W, we write the simple relation

$$\Delta U = A\Delta\Pi, \tag{3}$$

which relates the "jump" in $\Delta\Pi$ due to quasiadiabatic deformation to the corresponding value of ΔU. The coefficient A [1/Pa] is written as

$$A = A_r A_c A_m, \tag{4}$$

where A_r $[1/(\mathrm{W}\cdot\mathrm{m}^{-2})]$ is the coefficient of proportionality between ΔU and ΔW, determined from the characteristics of the receiver-amplifier equipment.

Temperature measurements using IR-radiometers are employed to determine elastic-stress variations in metals and polymer materials [13]. A relationship between variations in IR-radiation flux and stress variations in geomaterials was detected and investigated for the first time in studies at the Institute of Foundations and Underground Structures [8, 14].

In geomaterials, the temperature drops caused by their elastic deformation are rather slight and can be of the order of 10^{-4}–10^{-3} deg. At the same time, the above-mentioned studies showed that it is quite possible to determine such drops from IR-flux measurement data. The question is the measurement with such accuracy of slight variations rather than absolute values of temperature.

Unlike conventional methods of measuring stresses in geomaterials, the proposed approach allows one to perform noncontact measurements and to scan their results in time and space. In comparison with geomonitoring methods based on other physical principles [6, 7], the technique (in analysis of prelimiting stress variations in materials) is distinguished by a simple initial physical model. On the other hand, the main limitation of the approach, i.e., the possibility of determining only variations in the sum of principal stresses $\Delta\Pi$, is frequently unimportant.

To calculate $\Delta\Pi$ from measured values of ΔU, one should determine the value of A. To find A from formula (4), it is necessary to conduct special experiments and determine parameters, in particular, the thermal characteristics of ground or rock, on which the coefficients A_r, A_c, and A_m depend. A simpler method consists in testing a material sample under conditions where the value of $\Delta\Pi_f$ can be determined independently of IR-measurements. Then, detecting the value of ΔU_f that corresponds to $\Delta\Pi_f$ by a measuring system, it is possible to estimate the value of $A \approx A_f = \Delta U_f/\Delta\Pi_f$, which is necessary to interpret results of the main measurements using this system. Such calibration was performed in tests of some rocks under uniaxial compression [8].

Below, we describe results of compression tests of ground samples performed with the purpose of designing a series of elements of the technique (thermal-radiation measurements and determination of A_f for grounds, collection and analysis of data characterizing the time variation of load and corresponding variations in the IR-radiation flux, etc.). We used for the first time a specially designed measuring system, which incorporates in particular a highly sensitive radiometer combined in a unit with an amplifier having an increased signal/noise ratio. This unit is connected to a two-channel analog-to-digital converter (ADC) intended for measurements and automatic synchronous transmission of analog signals from an IR-radiometer and a strain-gauge element to a computer.

A diagram of a simple setup for loading samples and the arrangement of measuring gauges are shown in Fig. 1. Sample 1 about 35 mm high is located in rigid cylindrical casing 3 with inside diameter 98 mm and length 60 mm. Sandy ground samples were prepared by placing successive layers of purified quartz sand in the casing, and clay ground samples were prepared by forcing the casing into a "monolith" of clay paste with subsequent withdrawal of it together with the sample and levelling of its end surfaces. Rigid die 2 15 mm thick

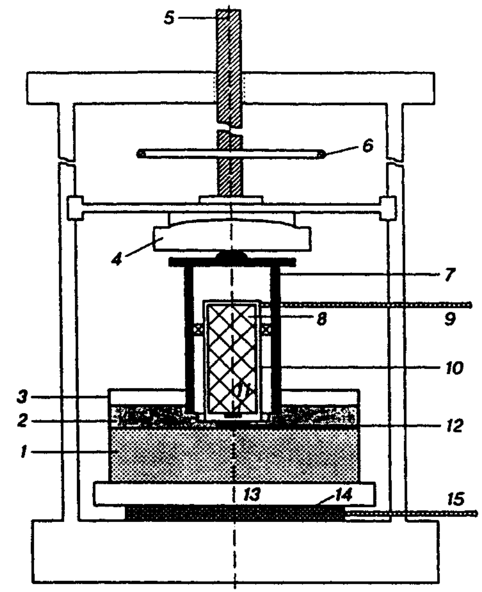

Fig. 1. Diagram of the setup used in tests of ground samples and measurements: 1) sample; 2) die; 3) casing; 4) press plate; 5) screw; 6) control wheel; 7) rod; 8) amplifier; 9 and 15) cables; 10) IR-radiometer; 11) receiver; 12) germanium plate; 13) rigid plate; 14) strain-gauge element.

is mounted on the sample. The diameter of the die is practically equal to the diameter of the sample, and the die enters the casing without friction along the lateral surface. The axial movements of the upper plate of press 4, caused by rotation of screw 5 by control wheel 6, are transmitted to the die through rod 7 with inside diameter 50 mm pressed in it. At the center of the die there is a through hole with diameter 23 mm covered from below by germanium plate 12 with fixed transmittance [12], through which the radiation flux from the sample surface enters the receiver 11 of IR-radiometer 10 placed inside the rod. A plate 2 mm thick and 25 mm in diameter "flush-mounted" with the bottom surface of the die prevents extrusion of the ground through the hole and provides a uniform pressure distribution under the die. The IR-signal passing through preamplifier 8, mounted inside the radiometer, is sent by cable 9, drawn through a hole on the rod wall, to the main amplifier with a frequency filter, and then to the first channel of the ADC, where it is digitized. The resulting values of pressure $V_w(t_k)$ are sent to the computer at times $t_k = k\Delta t$, where $k = 0, \ldots, N - 1$, Δt is a given step in time, and $N = T/\Delta t$ (T is the duration of the test).

From below, the sample and the casing are supported by rigid plate 13. Strain-gauge element 14 (force cell) is placed between this plate and the press plate to measure variations in the load on the sample. The signal from the strain-gauge element, proportional to its strain and, hence, to the load, is sent by the second cable 15 through the strain amplifier to the second channel of the ADC. Converted and amplified values of the voltage $V_g(t_k)$ of this signal are also transmitted to the computer in synchronism with values of $V_w(t_k)$. After several preliminary experiments, the value of Δt and the averaging interval for filtration of signals transmitted to both channels of the ADC were taken as 0.1 sec. The gains (10^6 for the signal from the IR-radiometer and 10^2 for the signal from the force cell), and also the levels of V_w^0 and V_g^0 at no-load were chosen so that graphical representation of both records in one scale within ± 3 V is made convenient.

During the experiment, the evolution of the functions $V_w(t)$ and $V_g(t)$ is tracked on the monitor screen, and the text file which records values of $V_w(t_k)$ and $V_g(t_k)$ is saved for subsequent processing. Such a file for each experiment is a sequence of numbers the first of which contains information on the experiment, and the subsequent even numbers ($i = 2k$) carry information on values of$V_w(t_k)$ and odd numbers ($i = 2k + 1$) are values of $V_g(t_k)$.

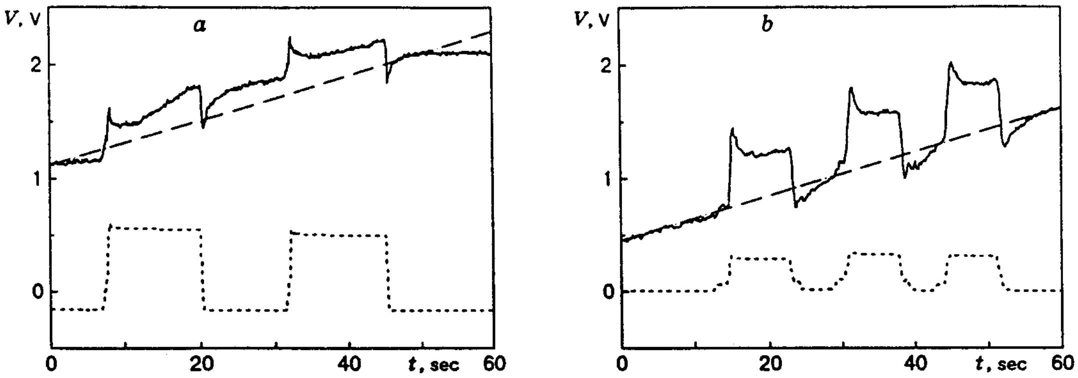

Fig. 2. Typical time variations of measured converted and amplified signals ($0 < t < 60$ sec) for sandy (a) and clay (b) samples: the solid curve is the signal from the IR-radiometer $V_w(t)$; the dashed curve is the signal from the force cell $V_g(t)$; and the dot-and-dashed curve is the linear approximation of $V_c(t)$ by the trend component $V_w(t)$.

Alternating cycles of loading and unloading, corresponding to the rotations of the control wheel executed by the operator, start 8–10 sec after the beginning of recording and recur 1–5 times within $T \approx 50$–100 sec. Figure 2 shows typical records of $V_w(t_k)$ (the solid curve) and $V_g(t_k)$ (the dashed curve) for one of the experiments with sandy (a) and clay (b) grounds.

We note peculiarities of the behavior of the functions $V_g(t)$ and $V_w(t)$. In short time intervals in which loading (or unloading) occurs, the values of $V_g(t)$ and $V_w(t)$ increase (or decrease) jumpwise. Then, the values of $V_g(t)$ remain almost constant within time intervals in which the load is constant, and they are almost exactly equal to V_g^0 when the load is equal to zero. Such a pulsed behavior of the function $V_g(t)$ allows one to detect first visually and then quantitatively intervals of loading, unloading, and stationary load.

It is seen from Fig. 2 that in intervals in which the values of $V_g(t)$ vary significantly and, hence, the load increases or decreases, the records of $V_w(t)$ and $V_g(t)$ are almost similar. After stabilization of the load, the values of $V_w(t)$, in contrast to $V_g(t)$, continue to change with change in the thermal conditions, tending to reach the values determined by the temperature balance of the sample with the ambient medium. The rate of such changes remains far lower than the rate of jumpwise changes in $V_w(t)$ at the moment of changes in load. This allows one to assume that the deformation of the sample is quasiadiabatic at the indicated moments.

Comparison of the records of $V_w(t)$ and $V_g(t)$ shows that data of IR-measurements can be used, at least, as an "indicator" of changes in the mechanical state of geomaterials. Quantitative processing of data of the tests was aimed at determining the relation between the magnitudes of the jumps in records of IR-measurements and the stress variation in the sample. A computational program was developed which took into account the pulsed nature of the record of $V_g(t)$ and features of the record $V_w(t)$. Local increments ΔV_g of the function $V_g(t)$ are first evaluated and analyzed, and then the time intervals in which ΔV_g are practically equal to zero (constant load), positive (load rise), or negative (unloading) are determined. The computer memory saves the initial values of $t_j^{\pm}$ and the duration $(\Delta t)_j^{\pm}$ of each interval in which loading (the plus sign) or unloading (the minus sign) occurs, and also the corresponding increments $\Delta_j V_g^{\pm}$ of the function $V_g(t)$.

In analysis of the IR-measurement data, it is necessary to take into account that, besides the "useful" component, determined by mechanical processes in the sample, they always include the "noise" component and can contain a "trend" caused by changes of external conditions. The trend component $V_c(t)$ in each record of $V_w(t)$ was evaluated from its rectilinear approximation through the initial (before the first loading) and final (10–20 sec after unloading) segments (see Fig. 2). Then, instead of $V_w(t)$, we consider the function $U(t) = V_w(t) - V_c(t)$, which practically does not depend on the trend.

For the intervals of load variations $(\Delta t)_j^{\pm}$ detected from the record of $V_g(t_k)$, the corresponding increments $\Delta_j U^{\pm}$ were determined. In the subsequent calculations, we took into account only the intervals $(\Delta t)_j^{\pm}$ on which these increments were not less than 0.5 of the maximum (in the absolute value) increment

$|\Delta_j U^{\pm}|_{\max}$ for the given experiment. This limitation seeks to "cut off" short intervals $(\Delta t)_j^{\pm}$ with small $\Delta_j U^{\pm}$, whose estimates can be strongly affected by random noise in the record of $V_w(t)$. For the set of intervals $(\Delta t)_j^{\pm}$ that satisfy the indicated limitation, we calculated the weighted mean values of $(\Delta V_g^{\pm})_e$ and $(\Delta U^{\pm})_e$ in each experiment. The ratio of these values

$$A_g^{\pm} = (\Delta U^{\pm})_e / (\Delta V_g^{\pm})_e \tag{5}$$

is an estimate of the derivative of change in the IR-measurement results from data of $V_g(t)$, which give information on load variation. The values of A_g^+ and A_g^- calculated from ratio (5) for the given experiments differ from one another by not more than 10%, except for one experiment where the relative difference is 35%. Furthermore, for each series of experiments, the spread of particular values of $\Delta_j U^{\pm}/\Delta_j V_g^{\pm}$, which were calculated for a fuller analysis of the data obtained, is insignificant. It is thus shown that for the same sample and the same test conditions, the variation in the reading of the IR-radiometer is proportional to the load variation.

At the same time, the values of $A_g = 0.5(A_g^+ + A_g^-)$ for different experiments differ considerably from each other. We performed nine experiments with samples of sandy and clay grounds. The average value of A_g was 0.63 for sandy grounds (the values varied from 0.33 to 0.97) and 2.13 for clay grounds (the values varied from 1.46 to 2.79). The conclusion that clay grounds show much higher thermomechanical activity compared to sandy grounds is of interest. Three experiments on samples of loamy grounds, performed to verify this conclusion, gave a value of $A_g \approx 1.35$, which is intermediate between the values obtained for clay and sand.

From the values of A_g, we determine the values of A, assuming that $\Delta U = \Delta(V_w(t) - V_c(t))$ in ratio (3). We express $\Delta\Pi$ in terms of the change in load ΔG

$$\Delta\Pi = (\Delta G/S)(1 + 2\xi), \tag{6}$$

where ξ is the coefficient of lateral pressure in the ground inside the casing and S is the area of the die. The relation between ΔV_g and ΔG is written as

$$\Delta G = k_{GV} \Delta V_g. \tag{7}$$

Substituting (6) and (7) into (3) and converting, we obtain

$$A = A_g S (k_{GV}(1 + 2\xi))^{-1}. \tag{8}$$

The value of the coefficient $k_{GV} \approx 6.6 \cdot 10^3$ N/V (for the specified amplification of strain-gauge signals in the experiments) is determined by preliminary calibration of readings of the force cell using readings of a reference dynamometer placed between the force cell and the press plate. Using $\xi \approx 0.5$ for sandy grounds and $\xi \approx 0.6$ for clay grounds, from formula (8) we find that the sought values are $A \approx 1.4 \cdot 10^{-6}$ and $4.3 \cdot 10^{-6}$ V/Pa, respectively. These values can be employed to interpret only IR-measurement data obtained using the same measuring system as in the experiments described here. Nevertheless, the fact that such measurements yield qualitative results (detection of the moments of changes in the state of geomaterials) as well as quantitative results indicates that the technique described here holds promise for geomechanical [8] and geophysical [9, 15] studies.

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