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# DETERMINATION OF PERIODIC CHANGES IN THE STRESS STATE OF GROUNDS FROM VARIATIONS IN INFRARED RADIATION FLUX

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*Examples of the records of variations with time in the signal from an infrared radiometer caused by the stress variations in the ground specimen and synchronous readings of strain gauges used to calculate stress variations are given. An algorithm of processing these records is constructed. A satisfactory coincidence of the stress variations in time determined with the use of synchronous radiation and tensometric measurement data is shown. The results show the efficiency of the infrared diagnostics of periodic changes in the stress state of grounds.*

The technique developed for the diagnostics of stress variations in grounds with time is based on the effect of temperature variation in an elastic medium upon adiabatic deformation [1] in which the increment of the first stress-tensor invariant $\Delta\Pi$ causes the increase in temperature at the point of the medium $\Delta T_a = A_m T_0 \Delta\Pi$, where $T_0$ is the initial absolute temperature and $A_m = \alpha/(\rho C_p)$ ($\alpha$ is the linear-expansion coefficient, $C_p$ is the specific heat at constant pressure, and $\rho$ is the density of the material). In this regime of deformation, the temperature variations $\delta_a T(t)$ in time $t$ are similar to the function $\delta\Pi(t)$ (with the similarity factor $A_m T_0$):

$$\delta_a T(t) = A_m T_0 \delta\Pi(t). \tag{1}$$

Obtaining information on $\delta\Pi(t)$ from $\delta_a T(t)$ measurements seems to be quite straightforward; however, for geomaterials the difficulty lies in the fact that the values of $\delta_a T(t)$ have the order 0.001 K. In addition, the conditions of real geomechanical and geophysical experiments do not allow one to use standard methods of temperature measurement [2], especially for measurements in grounds. These difficulties are overcome (see, e.g., [3, 4]) by the technique of measuring small temperature variations based on the dependence of the infrared (IR) radiation power from the body surface on its temperature $W(T) = \varepsilon_T \omega T^4$ ($\varepsilon_T < 1$ is the radiating-capacity coefficient and $\omega$ is the Stefan–Boltzmann constant) [5, 6]. Transforming $W(T(t))$ to the dependence $\delta W(t) = W(T(t)) - W(T_0)$, linearizing the corresponding $T_a(t)$ variations $\delta W_a(t) = \delta W(T_a(t))$ with allowance for the smallness of $\delta T_a(t)/T_0$, and denoting $A_c = 4\varepsilon_T \omega T_0$, we obtain

$$\delta W_a(t) = A_c \delta T_a(t)/T_0 = A_c A_m \delta\Pi(t), \tag{2}$$

i.e., $\delta W_a(t)$ and $\delta\Pi(t)$ are similar. Owing to the heat exchange in the nonadiabatic deformation regime and the constant $T_0$, for the temperature variations $\delta T(t)$, we have the equation

$$\delta T(t) = \delta_a T(t) + \delta_h T(t) = A_m \delta\Pi(t) T_0 + \delta_h T(t) \tag{3}$$

instead of (1). Here $\delta_h T(t) = \delta_h(T(t) - T_0)$ is the temperature variation necessary to restore the thermal equilibrium distorted by deformation [5]. It follows from (2) and (3) that

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$$\delta W(t) = A_c A_m \delta\Pi(t) + A_c \delta_h T(t)/T_0. \quad (4)$$

We assume that the component $\delta U_e(t)$ of the IR measurement-result variations, which is determined by the variations $\delta W(t)$, is proportional to them with the coefficient $A_r$ dependent on the instrumentation parameters; with allowance for (3) and (4), we obtain

$$\delta U(t) = \delta U_e(t) + \varepsilon(t) = \delta U_a(t) + \delta U_h(t) + \varepsilon(t) = A\delta\Pi(t) + A_r A_c \delta_h T(t)/T_0 + \varepsilon(t). \quad (5)$$

In relations (5), $\delta U_a(t)$ and $\delta U_h(t)$ are the terms of $\delta U_e(t)$ corresponding to $\delta_a T(t)$ and $\delta_h T(t)$ in (3) and $A = A_r A_c A_m$; the quantity $\varepsilon(t)$ takes into account the instrumentation noise in the function $\delta U(t)$, which describes the IR measurement results in the absence of external thermal effects. Using the functional dependences (1)–(5) between the variations $\delta U(t)$ and $\delta\Pi(t)$, one can make an attempt to identify continuous changes in the stress state of geomaterials in time on the basis of thermoradiation measurement data. (In [3, 4], Sheinin et al. used relations between the finite instantaneous increments $\Delta U$ and $\Delta\Pi$.)

Under conditions where the stresses change sufficiently fast in time, one can ignore the function $\delta_h T(t)$ and confine oneself to an analysis of measurement data under the assumption of quasiadiabaticity; here the function $\delta\Pi(t)$ is easily determined with the use of the experimental dependence $\delta U(t)$. To substantiate this assumption and determine the range of its applicability for various regimes of load variation in time, a series of experiments was performed, in which the stress variations were identified not only on the basis of IR radiation power measurements, but also on the basis of the readings of electromechanical gauges. In [3], the system of measurement, transformation, and automatic transfer, to a computer, of analog signals from an IR-radiometer $V_w(t)$ and a dynamometer $V_l(t)$ is used and the variations in load on the ground sample [7] are determined on the basis of the readings of this system. Processing of the synchronized recordings of the pulse load variations in time, which was performed in [3], showed that using thermoradiation measurement data, one can determine the moments of stress "jumps" in grounds and estimate their relative magnitudes.

In contrast to the experiments considered in [3], in the experiments described here the load on the sample and, therefore, the stresses in it were changed in time continuously according to a dependence close to a periodic one. The loading setup and the arrangement of measuring gauges are given schematically in [3]. The periodic character of the load changes in time was reached by smooth rotations of the steering wheel of a press performed for each 1.0–1.4 sec.

The values of the output signals $V_w(\tau)$ (in volts) obtained after passage of the primary signal from an IR radiometer through a preamplifier, the first channel of an analog-to-digital converter, and a finite amplifier are transmitted to the computer at the moments $\tau_k = k\Delta\tau$ ($k = 0, \ldots, N$, $N = \tau_N/\Delta\tau$, $\tau_N$ is the duration of the experiment, and $\Delta\tau$ is the given time step). The time reckoned from the moment of switching-on of the equipment is denoted by $\tau$. The transformed and amplified signals from the dynamometer $V_l(\tau_k)$ are transmitted to the computer synchronously with the output signals $V_w(\tau_k)$. The parts of the records before ($\tau < \tau_s$) and after the changes in loading ($\tau > \tau_f$) do not contain important information from the viewpoint of the identification of periodic stress variations. Therefore, below, we consider the functions $V_w(t)$ and $V_l(t)$ ($t = \tau - \tau_s$, $0 \leqslant t \leqslant L_t$, and $L_t = \tau_f - \tau_s$) in the time interval $\tau_s \leqslant \tau \leqslant \tau_f$ of duration $L_t$ during which the load variations occur.

The characteristic plots of the functions $V_w(t)$ and $V_l(t)$ obtained in the experiments with sandy ground are shown by curves 1 and 2 in Fig. 1. These plots are oscillatory. At the same time, there is a low-frequency component on both curves, which is determined by changes in the loading conditions for the output signal from the dynamometer $V_l(\tau)$. In addition to the low-frequency component connected with changes in loading, the IR-measurement data records can contain a component caused by changes in the external thermal conditions during the experiment, which is, in essence, the low-frequency noise. Figure 1 shows the low-frequency components $F_w(t)$ and $F_l(t)$ (curves 3 and 4) of the functions $V_w(t)$ and $V_l(t)$, for which the square approximation on the interval of definition of these functions was used. In a statistical analysis of measurement data, instead of $V_w(t)$ and $V_l(t)$, the functions

$$U_w(t) = V_w(t) - F_w(t), \qquad U_l(t) = V_l(t) - F_l(t), \quad (6)$$

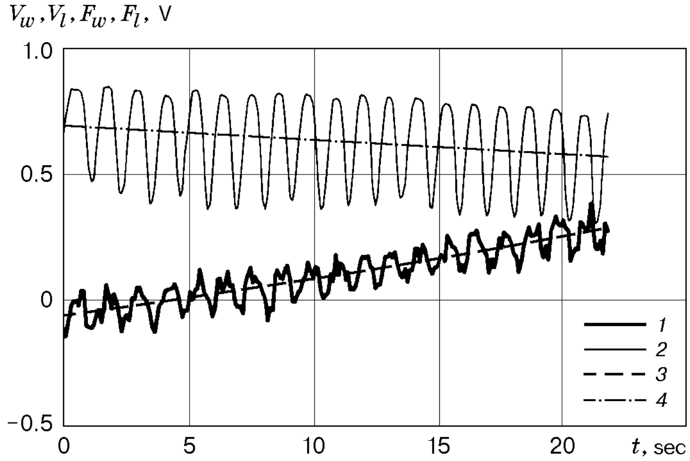


Fig. 1

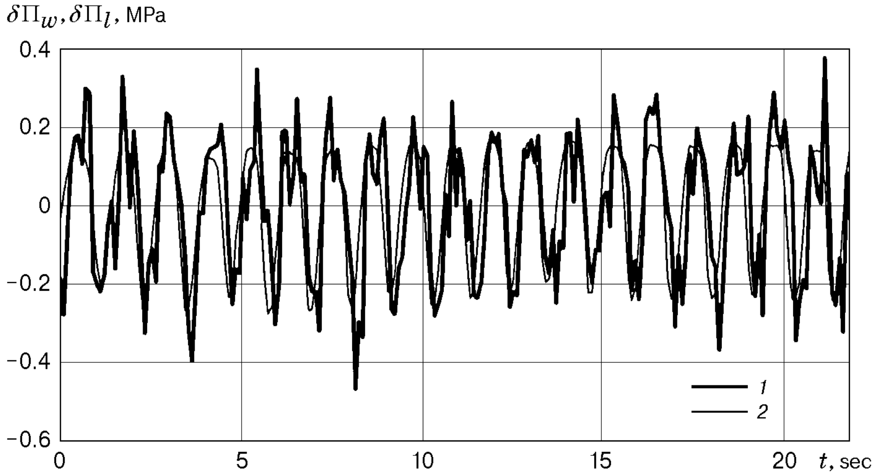


Fig. 2

which practically do not depend on the low-frequency component and have zero average values, were used.

Before each series of experiments, the output readings of the IR-radiometer channels $\Delta V_w$ and the dynamometer $\Delta V_l$ were calibrated with the use of the sum of the principal stresses $\Delta\Pi$ in the sample. To do this, stepwise loads $\Delta Q_m$, whose magnitude was determined by means of the readings of a standard load gauge installed between the dynamometer and the press plate, were applied to the sample. The quantity $\Delta\Pi_m$ corresponding to $\Delta Q_m$ was calculated from the formula

$$\Delta\Pi_m = (\Delta Q_m/S)(1 + 2\xi),$$

where $\xi$ is the lateral-pressure coefficient in the ground inside the cartridge and $S$ is the area of the pressing tool. Here, for each $\Delta\Pi_m$, the "jumps" of the levels of output signals from the radiometer $\Delta V_{wm}$ and the dynamometer $\Delta V_{lm}$ were measured. Then, the coefficients $A_{w\Pi} = A$ and $A_{l\Pi}$ of the transition from the variations in the output signals $\Delta V_w$ and $\Delta V_l$ (in volts) to those of $\Delta\Pi$ (in megapascals) were estimated by averaging the quantities $\Delta V_{wm}/\Delta\Pi_m$ and $\Delta V_{lm}/\Delta\Pi_m$. In the experiment with the sandy-ground sample ($\xi \approx 0.49$), we obtained $A_{w\Pi} \approx 0.28$ V/MPa and $A_{l\Pi} \approx 1.21$ V/MPa. Then, the variations

$$\delta\Pi_w(t) = U_w(t)(A_{w\Pi})^{-1}, \qquad \delta\Pi_l(t) = U_l(t)(A_{l\Pi})^{-1}, \tag{7}$$

whose plots for the experiment with sandy ground are shown in Fig. 2 (curves 1 and 2, respectively), were calculated. The amplitude of the functions $\delta\Pi_w(t)$ and $\delta\Pi_l(t)$ is of the order 0.3 MPa and they execute approximately 20 oscillations each for the time of the experiment (about 22 sec). The results of the other

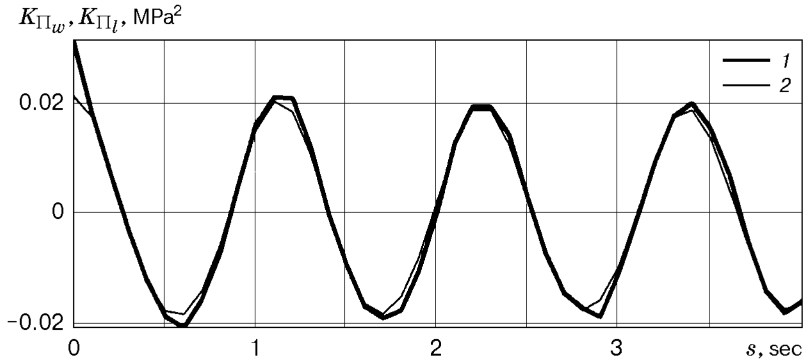


Fig. 3

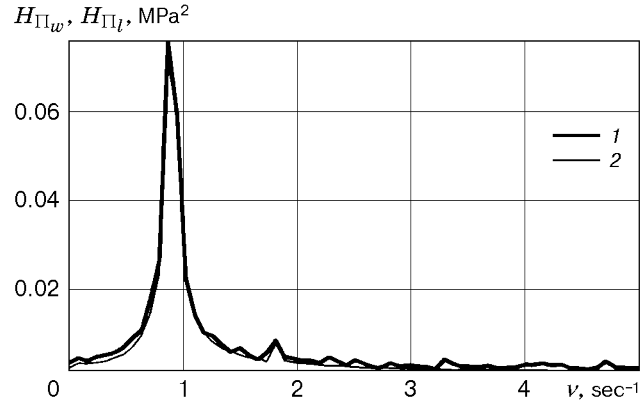


Fig. 4

experiments are similar to those given above (after appropriate transformations). One can see in Fig. 2 that the function $\delta\Pi_w(t)$ is quite close to $\delta\Pi_l(t)$.

To estimate quantitatively the difference between $\delta\Pi_w(t)$ and $\delta\Pi_l(t)$, a statistical analysis of these functions is required. In the time interval considered, the amplitude of the functions $\delta\Pi_w(t)$ and $\delta\Pi_l(t)$ varies insignificantly; therefore, in this interval, we regard them as the realizations of random stationary processes [8]. Let us calculate the probabilistic characteristics of these processes. The average values of $E_{\Pi_w}$ and $E_{\Pi_l}$ are equal to zero owing to the transition to the functions $U_w(t)$ and $U_l(t)$ by formulas (6), and the standard values of $S_{\Pi_w} = (K_{\Pi_w}(0))^{0.5} = 0.184$ MPa and $S_{\Pi_l} = (K_{\Pi_l}(0))^{0.5} = 0.147$ MPa differ by approximately 25%. The correlation functions were calculated from the formula

$$K_Y(s) = (M-m)^{-1} \sum_{i=1}^{M-m-1} (Y_i - E_Y)(Y_{i+m} - E_Y),$$

where $Y(t)$ is either the function $\delta\Pi_w(t)$ or $\delta\Pi_l(t)$, $s \in [0; 0.3L_t]$, $m = s/\Delta t$, and $M = L_t/\Delta t$. The functions $K_{\Pi_w}(s)$ and $K_{\Pi_l}(s)$ are plotted in Fig. 3 (curves 1 and 2, respectively). As is seen, curves 1 and 2 almost coincide for $s > 0.1$ sec, and the deviation near zero is determined by the influence of random high-frequency errors in the record of $V_w(\tau)$ [9]. We note that the results of the experiment in which the high-frequency noise component of this function (see Fig. 1) is observed even visually was chosen for illustration.

After the Fourier transform of the functions $K_{\Pi_w}(s)$ and $K_{\Pi_l}(s)$, we determine the spectral densities $H_{\Pi_w}(\nu)$ and $H_{\Pi_l}(\nu)$ [8, 9]. The dependences of $H_{\Pi_w}$ and $H_{\Pi_l}$ on the frequency $\nu$ are given in Fig. 4 (curves 1 and 2). The plots of the correlation functions and densities given in Figs. 3 and 4 almost coincide with those for the functions $\delta\Pi_w(t)$ and $\delta\Pi_l(t)$. A similar coincidence occurs in other experiments as well. It is important that the positions of the maxima of the densities $H_{\Pi_w}(\nu)$ and $H_{\Pi_l}(\nu)$ coincide in each experiment. Thus, the records of the signals from the IR radiometer allow us to estimate the statistical parameters of the stress evolution in time (see Figs. 3 and 4).

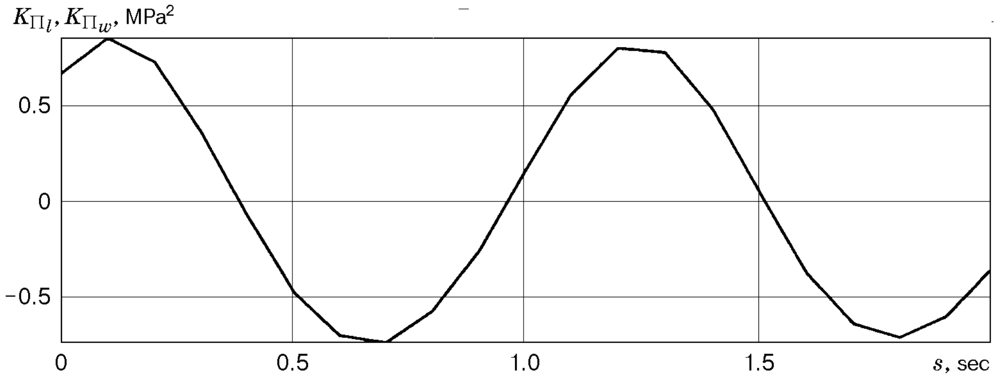


Fig. 5

In comparing the $\delta\Pi_w(t)$ and $\delta\Pi_l(t)$ plots, it is necessary to take into account their displacement relative to each other in time $t_0$. This time delay occurs because of the inertia of the primary IR-converter RTN-31 used [6]. To determine $t_0$, we estimate the mutual normalized correlation function $K_{\Pi_l\Pi_w}(s)$ of the dependences $\delta\Pi_w(t)$ and $\Delta\Pi_l(t)$:

$$K_{\Pi_l\Pi_w}(s_m) = ((M-m)S_{\Pi_l}S_{\Pi_w})^{-1}\sum_{i=1}^{M-m-1}\delta\Pi_{l_i}\,\delta\Pi_{w_{i+m}}.$$

The function $K_{\Pi_l\Pi_w}(s)$ is plotted in Fig. 5. According to [8], the value of $t_0$ corresponds to the position of the maximum of this function on the $s$ axis, i.e., $t_0 = 0.2$ sec. The function $\delta\Pi_w(t+t_0)$ is even closer to $\delta\Pi_l(t)$ than $\delta\Pi_w(t)$ (see Fig. 2).

The studies have shown the efficiency of the proposed technique and are of interest owing to the fact that the practical use of IR radiometry for field measurements of the variations in the stress state of ground massives can extend the possibilities of experimental observations of dynamic and seismic processes in them.

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