15°. Consequently, the considered jet contains 0.085 kg of hydrogen, whose mixture with air at the stoichiometric component ratio is equivalent energy-wise to a 0.85 kg mass of trotyl charge. The excess pressure dependence on r/r_0 in the SW which is produced in air during an explosion of the hydrogen-air mixture for the case investigated is presented in Fig. 7, curve 6. It is evident that the variation of the excess pressure, as described by the Sadovskii formula [6], disagrees with the results obtained by the numerical modeling of the fuel-air explosion. At short distances from the explosion site, for $r < (4\text{-}5)r_0$, the line 6 runs above the curves 1 to 4, i.e., the rise according to the Sadovskii formula overestimates the SW pressure. At greater distances, for $r > 10r_0$, the computation according to the Sadovskii formula underestimates the pressure in the SW at all levels above the ground surface. The computed Sadovskii variation does not take into account the different ways of reaching the maximum pressure in the air SW at various heights during the detonation of a hydrogen-air jet. Therefore, the pressure estimate of air shock waves during the detonation of gaseous jets using the Sadovskii formula leads to a significant discrepancy from the results, which are obtained by the numerical modeling process.

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ELECTRICAL FIELD ARISING DURING EJECTION EXPLOSION

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The underground explosion of an explosive charge, which causes strong deformations and disintegration of the material with the subsequent formation of an ejection cupola of soil and an expulsion of the explosion products (EP) into the atmosphere, is accompanied by the appearance of a low-frequency electric field (EF) in the ground-adjacent atmospheric layer. As a rule, in the explosions in earth having a moderate dampness, the EF signal has a bipolar characteristic [1], wherein the polarity of the first signal half-wave is negative (as the positive direction of the EF vector potential, one takes the top to bottom direction). The amplitude of the EF signal depends on the depth of the explosion and the distance to the measurement point. The period of the negative signal half-wave approximately corresponds to the development time of the ejection cupola and the scattering of the soil lumps. The second signal phase is related to the electric charge of the pulverized cloud produced during the explosion, and its duration is determined by the settling time of the particle cloud.

A typical time dependence of the vertical component of the EF E_z, as recorded during explosion ejections [1] is presented in Fig. 1 (curve 1). We calculate the evolution time of the electrical signal on the basis of a simple one-dimensional model for the motion of the earth ejection cupola and the explosion products (EP) without at first defining more precisely the particle electrification mechanism.

During the ascent of the earth ejection cupola, the earth particles and the gaseous explosion products are charged with opposite charges, with the earth acquiring a negative charge, as demonstrated experimentally. In the calculation of the EF potential far from the explosion epicenter, we assume that the entire soil with the charge $-Q_1(t)$ can be found at the upper point $H_1(t)$, while the EP and the dust form a narrow uniformly charged column with a height $H_2(t)$ and a total charge $Q_2(t)$. Then the vertical EF potential component on the

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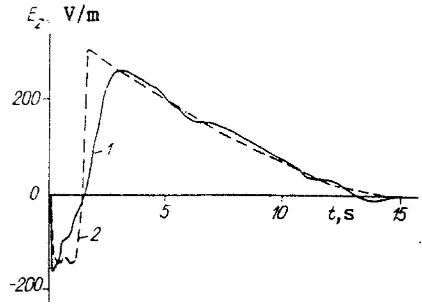

Fig. 1. Characteristic form of the E_z EF record in the near-ground atmospheric layer: 1) in an explosive charge explosion in sand having a mass of 0.0238 kg at a normalized depth of 0.68 m/kg$^{1/3}$ and at a 5.2 m distance; 2) computed $E_z(t)$ variation obtained from Eq. (1).

ground surface at a distance R from the explosion epicenter has the form

$$E_z = -\frac{Q_1 H_1}{2\pi\varepsilon_0 (H_1^2 + R^2)^{3/2}} + \frac{Q_2}{2\pi\varepsilon_0 H_2}\left(\frac{1}{R} - \frac{1}{(R^2 + H_2^2)^{1/2}}\right). \tag{1}$$

This equation includes the field of the electric charges induced in the earth, which has an ideal conductivity.

The heights of the ejection cupola's rise and of the dust-gas cloud can be described approximately by the functions $H_1 = H_2 = u_i t - g_0 t^2/2$, where u_i is the initial soil velocity, g_0 is a quantity, which is significantly greater than the free fall acceleration g. This is related basically to the air drag on the soil motion. Assuming that during the ascent phase the linear electric charge density in the dust-gas column remains unchanged, we get $Q_2 = -Q_1 = Q_0 H_2/H_m = Q_0(u_i t - g_0 t^2/2)H_m$, where Q_0 is the maximum charge at the height of the greatest rise H_m. For the soil descent phase, it is necessary to set in the expression for H_1, $g_0 = g$. In this case, the soil charge is $Q_1 = -Q_0$. The charge Q_2 is determined from the preceding formula, where H_2 is reduced by the settling of the dust-gas cloud particles. To describe this process, it is necessary to take into account the air drag forces acting on the charged dust particles.

We assume that the descent velocity and the particle dimension a are small, i.e., Re < 1. The equation of motion for the particles with mass $M(a)$ having a charge $g(a)$ will then have the form

$$\frac{d\vec{v}}{dt} = g - \frac{\vec{v} - \vec{u}_g}{\tau} + q\frac{\vec{E}_s}{M}, \quad \tau = \frac{M}{6\pi\eta a}, \tag{2}$$

where v is the particle velocity, u_g is the gas velocity, E_s is the intensity of the geo-electric and self-consistent EF of the charged particles and of the induced charges in the earth, and where η is the air viscosity coefficient. Using the values for the dust particle dimensions a = 20 μm, for the particle charge q = 100e (e being the elementary charge) and an EF intensity corresponding to the air breakdown condition E_b = 30 kV/m, we find that $qE_b/M = 0.7$ m/sec$^2 \ll g$, i.e., the effect of the EF on the motion of particles of such size can be neglected. Nevertheless, for finely dispersed dust with a large specific electrical charge, the effect of the EF factor in the motion can be significant.

By setting for simplicity $u_g = 0$ and integrating twice Eq. (2) over time from the instant the descent starts, we obtain the equation $H_2 = H_m + \tau g(u_i/g_0 - t)$. Equation (1) has the expressions for H_1, H_2, Q_1, and Q_2 at the various process stages described the EF during the explosion in the ejection. At the time instant $t = u_i g_0^{-1}(1 + \sqrt{g_0/g})$ the first term in (1) reduces to zero, while at $t_* = u_i g_0^{-1} + H_m(g\tau)^{-1}$ (complete precipitation of the dust-gas cloud), the field disappears, $E_z = 0$. Thus, a measurement of the EF relaxation time t_* makes it possible to estimate (in the absence of wind) the mean dimension of the charged dust particles.

Curve 2 in Fig. 1 shows the results of computations made in accordance with the derived formula, which are compared with the experimental variation. Parameter values $\eta = 1.7 \cdot 10^{-5}$ Pa·sec, and a = 48 μm were used in conjunction with the kinematic characteristics of the ejection cupola motion which were obtained from motion-pictures of the explosion development: g_0 = 23 m/sec^2 and u_i = 14 m/sec. The parameters Q_0 = 1.84 μC and H_m = 4.2 m were estimated from experimental amplitude values in the negative phase of the E_z signal using the least squares method [1]. It should be recognized that the shape of the initial half-way strongly depends on the charge distribution in the ejection cupola. Only at great distances R, where the dipole approximation is valid, the signal is smoothed out. The sharp peak in the second half-wave is a consequence of the approximation of a simultaneous descent of the soil particles.

We next estimate the effect of other mechanisms of producing an EF during an explosion in the ground. The initial electrical signal peak may be related to a perturbation of the Earth's electromagnetic field by a seismic wave, or may be caused by shock polarization from the detonation of the explosive and the propagation of a shock wave (SW) through the ground. We estimate the effect of the magnetoelastic wave with the aid of the relation $E_z \sim \mu_0 v_\ell H_3$, which is valid for frequencies $\omega < \mu_0 \sigma_e c_p^2$ [2], where H_3 = 40 A/m is the geomagnetic field intensity, v_ℓ is the velocity of ground movement, c_p is the sonic velocity in the ground, and σ_e is the electrical conductivity coefficient. For an explosion in sand with σ_e = 25 $1/(\Omega \cdot m)$ and $v_\ell \sim c_p \sim$ 100 m/sec, we find that $E_z \sim$ 0.5 mV/m, i.e., the effect is small.

The shock polarization on the SW front is proportional to the pressure amplitude. We estimate the maximum SW dipolar electrical moment p by integrating the modulus of the polarization vector over the volume with radius R_0 enveloping the SW [3]. By assuming that the pressure amplitude decreases with distance R from the explosion epicenter according to the equation $p = p_0(r_0/R)^n$, we obtain the estimate

$$E_z \sim \frac{P}{4\pi\varepsilon_0 R^3} \sim \frac{A p_0 r_0^n R_0^{(3-n)/3}}{\varepsilon_0 (3-n) R^3},$$

where p_0 and r_0 are the initial pressure and the dimension of the explosion chamber, and A is the coefficient of proportionality between the material polarization and pressure. By specifying $A \sim 10^{-5}$ C/(m^2·GPa), p_0 = 10 GPa, r_0 = 1.5 cm, R_0 = 10 cm, and n = 2, we find that at a distance R = 5 m, $E_z \sim$ 2 V/m which is two orders of magnitude smaller than the experimental value. We note that the piezoeffect in the case of an explosion in sand is not substantial, in spite of the fact that the piezo modulus of quartz is two orders of magnitude greater, than the A value. This is related to the circumstance that the quasistatic field observed in [1] is determined by the summed dipole moment of the sand particles. In view of the chaotic orientation of the quartz monocrystals in the sand particles, the total dipole moment caused by the piezoeffect equals zero.

The electrification of the soil during the explosion may also produce particle breakdown by friction. The value of the surface charge, which is produced in the cleaving of crystal surface is of the order of $5 \cdot 10^{-7}$ C/m^2 [4], which is close to the surface charge density of $\sim 10^{-6}$ C/m^2 in the experiment of [1]. The microcleavage and breakdown are related to the stress concentration on the contact surface of the soil particles. The local stress at the contact is expressed in terms of the mean stress on the soil p in the form: $p_\ell = p^{1/3} \times (4E/3\pi(1-\nu^2))^{2/3}$ [5], where E ~ 50 GPa is the Young modulus for quartz (for explosions in sand), and $\nu \sim$ 0.25 is the Poisson coefficient. For a breakdown to occur, it is necessary that $p_\ell \gtrsim$ 1 GPa, which means that p > 2 MPa. Such pressures are produced over sufficiently large regions behind the SW.

At the instant of the gas outburst through the ejection cupola, together with the EP, charged fragments of the disintegrated soil and dust particles are carried out. We define ρ_* as the charge density of the microparticles contained in the EP. Then, from the time the motion starts through the ejection cupola surface having an area S(t), an electrical charge $Q \sim \int_0^t \rho_* S v_p \, dt$ is carried away. The relative explosion product velocity v_p on the cupola surface is proportional to $\Delta p/\Delta h$, where Δp is the pressure drop over the cupole thickness Δh. For ejection explosions, where the same normalized depth of the deposited explosive charge is used, the motion characteristics possess similarity. In particular, $S \sim C^{2/3}$, $\Delta h \sim C^{1/3}$, and $t \sim C^{1/3}$ (where C is the mass of the explosive charge, and t is the time of the gas breakthrough), while ρ_* and Δp are practically independent of C. Taking these relations into account, we find that $Q \sim C^{2/3}$, where as the experimental data yield the relation $Q = KC^{0.5\pm0.085}$ [1]. Nevertheless, keeping in mind the approximate nature of the estimate, this mechanism of soil electrification during the explosion cannot be excluded.

The experimental dependence can be properly explained by considering the interaction between the soil and the ionized products of the explosive charge detonation. This process is characteristic of the initial explosion phase, when the detonation products are separated from the surrounding medium by a soil layer. The partial ionization is produced by the formation of chemical free radicals and by the thermal ionization, with the initial electron concentration reaching 10^{18} to 10^{20} cm^{-3} [6]. Up to the instant when the ejection cupola disintegrates into individual parts, the detonation products diffuse into the soil mass through cracks and cavities, which are formed during the explosion. The crack surfaces can capture electrical charges of one sign, as a consequence of which, the soil acquires a charge. The gas filtration velocity u_f is determined by the pressure p in accordance with the generalized Darcy law. In the reference system linked to the soil, we have

$$-\nabla p = \frac{\eta}{k_\ell}\vec{u}_f + \frac{\rho_g}{k_f}\vec{u}_f|\vec{u}_f|, \tag{3}$$

where k_ℓ and k_t are the laminar and turbulent penetration coefficients, and ρ_g is the gas density. For a medium with a high porosity m, the empirical relation between the parameters is of the form $k_t = 200m^{5.5}\sqrt{k_\ell}$ [7]. Under normal conditions ($\eta = 1.7\cdot10^{-5}$ Pa·sec, $\rho_g = 1.2$ kg/m³), $m = 0.4$, and $k_\ell = 2\cdot10^{-14}$ m², the laminar term in (3) is larger than the turbulent one up to a velocity $u_f < 130$ m/sec. However, during the initial explosion phase, when the gas density decreases by two to three orders of magnitude, while the viscosity coefficient drops only by one order, a turbulent filtration regime is possible.

We estimate the volume of soil V, which interacts with the ionized detonation products. In the laminar regime, the penetration depth of the diffusion front during time t is $r_d \sim \sqrt{Dt}$, where $D \sim k_\ell p/\eta$ is the coefficient of the gas diffusion through the cracks. By specifying $p = 10$ to 10^{-3} GPa, and $t = 1$ msec, we find that $r_d \sim 10$ to 0.1 cm. In the case of large pressure gradients, or high soil porosity, when the turbulent regime predominates, the estimates based on (3) yield $r_d \sim (k_t p t^2/\rho_g)^{1/3} \sim 0.4$ cm. Using these estimates and taking into account the similarity of the characteristic values during the explosion ($t \sim C^{1/3}$, $S \sim C^{2/3}$), we obtain the necessary relations: $V \sim Sr_d \sim C^{5/6}$ for the laminar diffusion and $V \sim C^{8/9}$ in the case of the turbulent filtration regime.

A part of the electrical charges contained in the gas, which has penetrated into the coil, settles on the medium surface. The free electrons found primarily in the detonation products, are captured in 10^{-8} to 10^{-9} sec by the oxygen molecules. The relaxation time of ion charges due to the electrical conductivity of the weakly ionized gas is $\tau \sim \varepsilon_0\sigma\sqrt{MkT}/\alpha e^2$ (where σ is the cross-section for ion collisions with neutral particles, M is the ion mass, and α is the degree of ionization). Assuming that $\sigma \sim 10^{-17}$ m², $T \sim 10^3$ K, and $\alpha \sim 10$, we find that $\tau \sim 10^{-8}$ sec, i.e., the plasma remains quasineutral for $t > \tau$. The distribution according to velocity becomes Maxwellian after a time $\tau_M \sim \sqrt{M/kT}/n\sigma < 10^{-11}$ sec (n being the neutral particle concentration).

We assume that apart from the neutral molecules, the gas contains two types of ions. The concentrations of ions n_1 (charge −e) and n_2 (charge +e) are the same at the initial time instant and later change due to the processes of recombination and capture in electron traps on the crack surface layer. For the ion concentration between the crack walls we have

$$\frac{\partial n_1}{\partial t} + \operatorname{div}\vec{j}_1 = \mu_r n_1 n_2 - \mu_c n_1 (N_t - n_t)/d + \nu n_t' d, \tag{4}$$

$$\frac{\partial n_2}{\partial t} + \operatorname{div}\vec{j}_2 = -\mu_r n_1 n_2. \tag{5}$$

In the above equations, n_t is the surface concentration of traps which are filled with electrons. $(N_t - n_t)$ is the surface concentration of vacant traps, μ_r is the recombination constant, μ_c is the constant for electron capture by the traps, ν is the frequency of trap ionization, and d is the distance between the crack opening edges. The particle flux densities $\vec{j}_1$ and $\vec{j}_2$ are determined by the gas filtration and, if free electrons are present, also by the ambipolar diffusion. Within the framework of the problem being addressed, it is important to take into account the processes of recombination and capture, therefore we neglect the spatial variation of concentration by omitting the terms $\operatorname{div}\vec{j}_{1,2}$ from Eqs. (4) and (5).

The condition of quasineutrality of the plasma and the crack walls has the form $n_1 + m_t = n_2$, where $m_t = n_t/d$. Taking into account that $m_t \ll n_1$, and $m_t \ll n_2$, in (5) we set $n_1 = n_2$. Integrating Eq. (5) over time with the initial condition $n_2(0) = n_0$, we find that

$$n_2 \sim n_1 = n_0(\mu_r n_0 t + 1)^{-1}. \tag{6}$$

For dissociative recombination the process constant is $u_r \sim 10^{-6}$ to 10^{-7} cm³/sec. Postulating that $n_0 \sim 10^{15}$ to 10^{18} cm^{-3}, we note that for $t \gg (n_0\mu_r)^{-1} \sim 10^{-8}$-$10^{-12}$ sec, it is permissible to neglect unity in the denominator of Eq. (6).

By subtracting Eq. (4) from (5) and taking into account that $N_t \gg n_t$, we obtain

$$\frac{dn_t}{dt} = \mu_c N_t n_1 - \nu n_t. \quad (7)$$

The frequency of the thermal trap ionization is $\nu = \nu_0 \exp(-E_c/kT)$, where $\nu_0 \sim 10^{13}$ sec^{-1}, while the energy of the capture level $E_c \sim 0.1$ to 0.5 eV. For $T \sim 10^3$ K we find that $\nu^{-1} < 10^{-10}$ sec, which is much shorter than the characteristic explosion development period t ~ 1 msec. The derivative in (7) is therefore much smaller than the second term on the right-hand side of the equation and can be omitted. As a result, from Eqs. (6) and (7) we find that

$$n_t \approx \frac{N_t \mu_c}{\nu \mu_r t}.$$

The obtained relation makes it possible to estimate the charge which is captured by the scattered medium: $Q \sim -emn_t V/d$, where V is the volume of soil which is interacting with the ionized detonation products. Using the above-obtained results, we obtain the following characteristic relations: $Q \sim C^{1/2}$ (laminar filtration regime); $Q \sim C^{5/9}$ (turbulent filtration regime), which are in good agreement with experiments [1], where an empirical dependence $Q \sim C^{0.5 \pm 0.085}$ was established for the maximum electric charge appearing in the epicentral region during explosions in sand and in sandy soil.

The analysis performed herein shows that the EF in the near-ground atmospheric layer, which appears during the explosions of explosive charges in soil, is related to the motion of the electrically charged ejection cupola and of the dust-gas cloud. The calculation of the $E_z(t)$ variation according to Eq. (1), taking into account the mechanisms of soil motion and the settling of the charged dust-gas cloud on the ground, agrees with experimental data. The investigation showed that the effects of shock polarization of the medium, and the perturbations of Earth's electromagnetic field by the seismic waves lead to much smaller EF values during the explosion. The electric charge of the soil may reach values which are obtained in tests due to the processes of breakdown and friction of the soil particles, however, its dependence on the mass of the explosive differs from the empirical one. A physical mechanism is proposed for the separation of electric charges during the filtration of the explosion products into the medium, which is broken down by the explosion. This mechanism takes into account the relaxation process in the plasma and allows to explain the experimental relation between the electric charge of the ejection cupola and the mass of the explosive.

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