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ELECTROSTATIC METHOD FOR DETERMINING THE PREDISPOSITION OF SOIL TO DEFLATION

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The equation of motion of soil particles in an inhomogeneous electrostatic field has been considered and solved numerically. The factors determining the rate at which particles are carried away from the field have been established. It is shown that the processes of the carrying away of particles in the electrostatic field and under the action of the air flow have analogs. The theory is intended to substantiate the rapid method of determination of the predisposition of soils to wind erosion under natural conditions.

One of the key problems in agriculture in the steppe, semiarid, and arid zones is the protection of fields against deflation. Direct in-the-field determination of the disposition of soils to deflation is carried out with the use of field wind tunnels and under laboratory conditions — in stationary aerodynamic facilities on soil samples. The legitimacy of extending the results of both variants of tests to concrete fields is questionable because of the large spread in results obtained in different aerodynamic facilities and by different researchers.

Of practical interest is the possibility of estimating the liability of soils to deflation directly in the field by means of a compact portable device and the possibility of unifying this operation.

The process of dispersion of the upper layer of the soil is associated with the movement of particles after their separation induced by wind flow. They move in either a rolling or bobbing manner or in suspension in the flow itself, decreasing the kinetic energy and the flow rate of the latter. In so doing, the major part of them move in a bobbing manner. Two reasons for the separation of the static particle are distinguished: rolling due to the air flow pressure and rise due to the pressure of the air that arises as a consequence of the velocity difference at the top and base of the particle. Of no less importance here is the role of the air pressure in the pores, which also contributes to the particle separation from the surface and the onset of motion perpendicular to it. Bobbing leads to the fact that the particle leaves the laminar layer and is picked up by turbulence pulsations [1, 2].

The erodibility characteristics of soils are: (1) critical velocity, or velocity of onset of deflation v^*; (2) rate of carrying away, or the amount of the substance carried away from a unit area in a unit time M^*; and (3) percentage of particles smaller than 1 mm. The first characteristic depends on the size and percentage of the fraction with particles and microaggregates smaller than 1 mm. It varies between 3 and 8 m/sec for soils of different granulometric compositions. The second characteristic is determined by the air flow rate v. The deflation also depends on the amount of physical clay, with whose decrease the probability of the appearance of erosion increases and at a content of less than 45% reaches its maximum.

As a rule, the soil layer being deflated is in the air-dry state and the interaction between particles is determined not only by the capillary forces. This fact permits using high-strength electrostatic fields to create electric forces overcoming the adhesion and gravitational forces that keep the soil particles in contact with one another. In other words, replacement of aerodynamic forces by electrostatic ones occurs.

The behavior of soil particles exactly in high-strength fields is of interest because of the change in their physicochemical properties. With adequate strength and relative position of electrodes it is possible to create controlled conditions under which particles of a certain size will separate from the soil surface and move in the electrostatic field for distances determined by their size, mass, strength, and the electrostatic field configuration.

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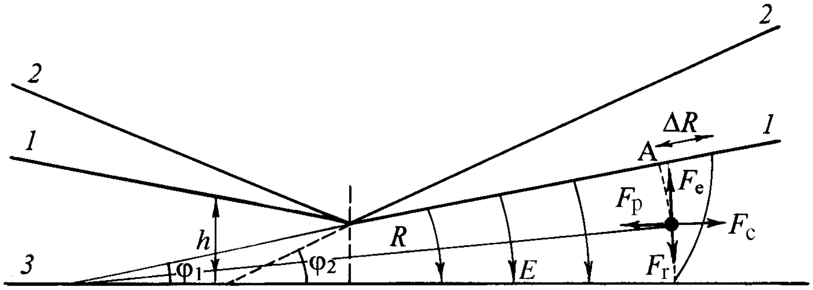

Fig. 1. Arrangement of electrodes, mechanical trajectory, and forces acting on the particle: 1, 2) potential cone-shaped electrodes with different angles between elements; 3) grounded electrode.

Over the soil surface (see Fig. 1), a convex electrode is located. The second electrode in the form of a ring is superimposed on the soil layer or on the layer of the air-dry-state soil sample. A voltage of a few kilowatts is applied to them. Since the conductivity of the soil particle surface is much higher than the air conductivity, the charge arising in the particle will be as if it were made of a conducting material [2, 3]:

$$q = \frac{2}{3}\pi^3 \varepsilon_0 r^2 E\,. \tag{1}$$

On the side of the electrostatic field the particle will be subjected to the action of the force $F = qE$ trying to separate it from the soil surface. When the condition

$$F_e \geq mg + F_a \tag{2}$$

is met, the particle will separate from the surface and start moving towards the upper level. Thus, there arises a force equivalent to the aerodynamic force formed due to the velocity difference at the top and base of the particle and acting perpendicular to the motion of air.

The electrostatic field in such a system has a grad (E) directed to the center of the electrode. Therefore, the soil particles will follow a curved path. They will be subjected to the action of the following forces: F_e, F_r, F_p, and F_c (see Fig. 1). In the case of $F_c > F_p$, the particles leave the interelectrode space and escape to the zone situated outside the upper electrode projection. Determining the voltage at which they begin to separate from the surface and move to the upper electrode or collecting the particles escaped per unit time and establishing their mass, one can judge the strength of their links with one another and, accordingly, the predisposition of soils to be dispersed by the wind flow.

We first establish the factors determining the rate of particle escape from the interelectrode space. To this end we consider the following expression describing the particle motion along the line of force:

$$m\frac{dv}{dt} = F_e - F_r\,, \tag{3}$$

where

$$F_r = C_x \frac{\rho\pi r^2 v^2}{2} = \frac{\pi\eta^2}{8\rho} C_x \,\mathrm{Re}^2\,; \tag{4}$$

$$\mathrm{Re} = \frac{2rv\rho}{\eta}\,. \tag{5}$$

In the range of Re = 1–1000, the resistance coefficient can be approximated by the dependence of the form $C_x = 17\ \mathrm{Re}^{-0.6}$. Substitute this value into (4) and then relation (4) into (5). Dividing both sides of Eq. (5) by m and introducing the coefficients

$$A = 8.5\pi r^{1.4}\,\frac{3\rho^{-0.6}\eta^{0.6}}{4\pi r^{3}\rho_{\mathrm{p}}} = 6.4\rho^{-0.6}\eta^{0.6}r^{-1.6}\rho_{\mathrm{p}}^{-1}\,, \quad B = \frac{2}{3}\,\frac{\pi^{3}\varepsilon_0 r^{2}E^{2}}{(4/3)\,\pi r^{3}\rho_{\mathrm{p}}} \pm g = 0.5\pi^{2}\varepsilon_0 r^{-1}\rho_{\mathrm{p}}^{-1}E^{2} \pm g\,,$$

we obtain the equation of particle motion

$$\frac{d^2x}{dt^2} - A\left(\frac{dx}{dt}\right)^{1.4} + B = 0\,. \tag{6}$$

We solve the second-order equation (6) by numerical methods and then determine the rate of particle motion in the interelectrode space as a function of time and the time Δt in which the particle covers the interelectrode spacing.

To solve this problem, it is necessary to make a number of assumptions: (a) the lines of force of the electric-field strength represent arcs of radius R; (b) the field strength at a distance ΔR from point A remains unaltered; (c) the velocity v varies by the linear law in the initial portion of the path and the times of arched motion and along the new path are equal. All these assumptions were used, for example, in [14] to substantiate the method for determining the specific charge of particles.

Figure 1 shows that the particle moves under the action of two forces: the centrifugal force F_{c} and the polarization force F_{p} along a path with a time-dependent radius of curvature R. In the time of motion t the particle moves a certain distance ΔR from the point A through which the line of force of the field passes.

Since $R \neq \mathrm{const}$, $\alpha_R = dv_R/dt = d^2R/dt^2$. Therefore, the distance ΔR can be found by the integration

$$\Delta R = \int_0^t \left(\int_0^t a_R\,(t)\,dt \right) dt\,. \tag{7}$$

The limits of integration are given on the basis of the solution of Eq. (6).

In accordance with the dynamic laws the radial component of acceleration in moving in a circle can be found from the relation

$$a_R = \frac{F_{\mathrm{p}}}{m} - \frac{v^2}{R}\,. \tag{8}$$

The polarization force

$$F_{\mathrm{p}} = 2\pi\varepsilon_0 r^3\,\mathrm{grad}\,(E^2) = 2\pi\varepsilon_0 r^3 E^2\,\frac{(2h + \varphi L)}{(h + \varphi L)^2} \tag{9}$$

is much smaller than all the other forces and does not need to be taken into account, as the analysis shows [9]. It has been found by experiment that under the action of this force a certain number of particles are drawn-in into the central region of the interelectrode space. This holds true for particles that are at unstable equilibrium where the electric force has completely balanced the gravity and adhesive forces but has not yet exceeded them and has not become strong enough to accelerate the particle.

The results of the calculation are given in Table 1. It is seen that as both the electric-field strength and the particle radius increase, the displacement ΔR increases. It is particularly strongly influenced by the path radius. It can be changed by varying the shape of the electrode. It is possible to obtain the minimum radius with the use of a spherical electrode.

TABLE 1. Calculated Parameters of the Particle Motion in an Inhomogeneous Electrostatic Field. The Particle Density is $2.65\cdot10^3$ kg/m^3 at R = 2.5 cm, $\varphi = 22^{\circ}$ and R = 5 cm, $\varphi = 11^{\circ}$, E = 10 kV/m, the trajectory length is 1 cm at R = 5 cm, $\varphi = 22^{\circ}$ and R = 10 cm, $\varphi = 11^{\circ}$, E = 10 kV/m, and the trajectory length is 2 cm

$E\cdot10^6$, V/m	$R\cdot10^{-2}$, m	$r\cdot10^{-6}$, m	A, $(\mathrm{m/sec}^2)^{-1.4}$	B, m/sec^2	t, sec	v_f, m/sec	τ, sec	v_R, m/sec	v_y, m/sec	$\Delta R\cdot10^{-3}$, m
1	5	10	240	1646	0.0045	3.6	0.0022	0.55	3.9	0.8
1	5	30	41	550	0.0063	3.2	0.01	0.7	6.4	1.6
1	5	100	6	164	0.011	1.8	0.055	0.14	10	1.8
1	5	500	0.44	22.6	0.03	0.65	0.35	0.12	17.5	1.2
0.5	10	10	240	412	0.016	1.5	0.003	0.18	1.5	0.9
0.5	10	30	41	137	0.019	1.7	0.015	0.3	2.4	2
0.5	10	100	6	41	0.037	1.3	0.082	0.36	3.7	4.8
0.5	10	500	0.44	2	0.14	0.28	1.21	0.25	2.9	2.7
1	2.5	10	240	1646	0.0043	3.5	0.0022	1.1	3.7	1.7
1	2.5	30	41	550	0.0064	3	0.01	1.2	6.4	2.5
1	2.5	100	6	165	0.011	1.8	0.055	0.75	11	2.9
1	2.5	500	0.44	22.8	0.029	0.64	0.35	0.28	17.5	2.7
0.5	5	10	240	412	0.016	1.5	0.003	0.43	1.5	2.5
0.5	5	30	41	137	0.019	1.8	0.015	0.6	2.4	2.9
0.5	5	100	6	41	0.032	1.3	0.082	0.65	3.7	5.6
0.5	5	500	0.44	2	0.14	0.28	1.21	0.11	2.9	5.4

It should be noted that for particles with a radius of 10 μm the velocity becomes constant with time. The other particles fly up to the opposite electrode with acceleration. The functions $v(t)$ can be approximated by an exponential law with a time constant τ depending on the particle size and the electric field strength:

$$\tau = \tau_0\,(r/r_0)^{1.4} + f(E)\,. \tag{10}$$

An experimental check of the method was carried out on a model with electrodes differing in shape — conical and spherical ones. The application of the spherical electrode has made it possible to simultaneously increase the angle and decrease the radius of the mechanical trajectory (see Fig. 1). The distance from the electrode top to the soil surface was 1–2 cm, and the voltage was varied from 4 to 20 kV. As soil samples, sand, loam, ordinary black earth, and ash from the dump of a thermal power station were used. The dependences of the rate of carrying away M on the electric-field strength and the exposure time have been investigated. In so doing, analogous measurements of the rate of carrying away M^* were made simultaneously on an aerodynamic stand depending on the air-flow rate and time. Analysis of the dependences of the rates of carrying away $M(E)$ and $M(t)$ compared to $M^*(v)$ and $M^*(t)$, respectively, points to their similarity. For instance, by analogy with the wind flow, there is a certain critical value of the electric-field strength at which the process of motion of particles begins.

Usually the rate of carrying away of particles in the electric field decreases with time due to the decrease in the number of particles capable of separating from the soil layer; therefore, it is the higher, the shorter the time interval.

Since in both cases we are interested in the number of particles capable of starting movement, we can determine the equivalent values of the wind-flow rate and the electrostatic-field strength on the basis of equality of the soil masses carried away by the aerodynamic and electrostatic forces. The equality of M and M^* from a unit area of the surface has made it possible to determine the wind-flow rate equivalent to a given strength.

Moving particles carry charges on them and in the chain transport current, or convective current, is formed. Inclusion in the chain of a microamperemeter makes it possible to note the beginning of the separation of particles and monitor the development of the scattering process in the course of time.

Moreover, as experiments have shown, the electric field permits a smoother action on the soil compared to the air flow in the wind tunnel. This is explained by the fact that the energy of the wind flow causing erosion is much higher than needed for such an amount of soil to be transported and the slightest change in the experimental

TABLE 2. Values of Critical Velocities Obtained in the Wind Tunnel at a Height of 12 cm (v^*) [6] and by Calculation by Dependence (12) at a Height of $2r$ (v^*_{e1}) and by Dependence (13) at a Height of 12 cm (v^*_e)

Size of the sand fraction	v^*, m/sec	z_0, mm	$E\cdot10^6$, V/m	v^*_{e1}, m/sec	v^*_e, m/sec
<0.1	3–3.5	0.01	0.32	0.85	3.6
<0.25	4.1	0.025	0.4	1.12	4
0.25–0.5	4.8	0.05	0.5	1.35	4.6
0.5–1	5.8	0.1	0.75	1.9	6.1

conditions causes considerable changes in the results. In the electrostatic field, practically all energy is expended in transporting particles and a change in the experimental conditions has a smaller effect. Therefore, this method can be considered with the object of unifying the process of determination of the predisposition of a soil to deflation.

Many authors ascertain that in the initial stage, upon the separation by the air flow, particles move practically vertically [1, 2]. Following this statement, compare the energy estimates of these two processes. In the region of rates close to the critical one, the kinetic energy of a moving two-phase system will be determined by the rate of motion and the mass of air, since the particle concentration is still very small. In [1], it is emphasized that the kinetic energy of the particles that have escaped from the surface should form a certain part of the kinetic energy of the air flow reaching the level of the tops of grains of sand, i.e., at a height of $2r$. According to the data of Table 1, the calculations of the energy expended by a particle in overcoming the friction force show that it is significant only for particles up to 0.06 mm in size. Therefore, the energy dissipation to heat can be neglected and it can be considered that the whole energy of the air flow is transferred to the particle for its acceleration. Because of its sluggishness, the air-flow meter usually determines a certain mean value (usually the acting one). On the condition that for the wind flow and the electric field the same energy is required to set particles in vertical motion (work function), one can equate the energy density of the electrostatic field to the kinetic energy density of the wind flow at a height $z = 2r$ at the moment the particles start moving:

$$\varepsilon\varepsilon_0 E^2/2 = \rho v^2/2\ . \tag{11}$$

Taking into account that the particle concentration in the electric field is as low as in the air flow and does not influence the air permittivity, the relation between the field strength and the air-flow rate will be as follows:

$$v = E\sqrt{\frac{\varepsilon\varepsilon_0}{\rho}}\ . \tag{12}$$

This relation has a physical meaning, since in hydrodynamic problems the velocity distribution around a moving liquid sphere is considered as an analog of the electrostatic field around the sphere [5]. The coefficient on the right side of dependence (12) plays the role of a certain equivalent relating the energies of the air flow and the electric field that are capable of doing equal work to move the particles of dispersive materials. The calculation shows that for air

$$\sqrt{\frac{\varepsilon\varepsilon_0}{\rho}} = 2.7\cdot10^{-6}\ \mathrm{m/(V\cdot sec)}\ .$$

The critical velocity is the most informative characteristic of deflation. Moreover, its determination by (12) is least dependent on the area and shape of electrodes as opposed to the rate of carrying away.

Compare the values of the critical velocity obtained by the electrostatic method with the use of (12) for the height $z = 2r$ with the data obtained in [6] for sand at a height of 12 cm with the aid of an anemometer. To this end, it is necessary to transform the velocity to one and the same height by the dependence, taking into account the logarithmic profile of the change in the velocity with height [1, 6]:

$$v = v_1 \ln\left(\frac{z}{z_0}\right) \Big/ \ln\left(\frac{z_1}{z_0}\right), \tag{13}$$

where v_1 is the velocity at height z_1.

If we take the roughness factor for each fraction in the relation $z_0 = 0.2r_{\max}$, then the values of the critical velocities determined in the wind tunnel and in the electrostatic field are practically the same (see Table 2).

Results. On the basis of the solution of the differential equation of motion of soil particles in the electrostatic field, the velocities and times of their stay in the interelectrode space have been determined, the forces acting on the particle during its motion along a curved path have been analyzed, and the factors influencing the rate at which particles are carried away from the interelectrode space have been determined. It has been proved by experiment that the dependences of the carrying away of soil particles in the electrostatic field and under the action of the air flow are analogous; it is possible to calculate the critical velocity on the basis of the determination of the field strength at which particles start separating from the surface.

The proposed theory and the facility developed on its basis can be used for rapid in-the-field determination of the liability of soils to deflation. The facility is very easy to use and reliable and is car-battery operated. It also makes it possible to carry out investigations of soil-protective agricultural techniques connected with mechanical working of the field surfaces and the application of artificial chemical structure formers.

NOTATION

v^*, critical velocity; M^*, rate of carrying away of a substance by the air flow; M, rate of carrying away of particles in electric field; r, particle radius; E, field strength; q, electric charge; $F_e = qE$, electrostatic force acting on a particle; F_r, force of resistance to viscous friction; mg, gravity force acting on a particle; F_a, particle-soil cohesion force; F_p, force caused by the particle polarization in an inhomogeneous electric field; F_c, centrifugal force; m, particle mass, v, velocity; t, time; C_x, resistance coefficient; Re, Reynolds number; R, radius of the path of motion of a particle; ΔR, radial displacement of a particle in one flight; α_R, value of the radial component of acceleration; r_0, certain initial value of the radius; h, minimum spacing between electrodes; L, length of electrode elements; v_s, stationary value of the rate of motion of particles at $F_e = F_r$; $r_{\max}$, maximum size of particles in the fraction; v_k, velocity at which the particle flies up to the electrode; v_R, radial shift velocity of a particle as it approaches the electrode; v^*, critical velocity obtained in the wind tunnel at a height of 12 cm [6]; v^*_{e1}, critical velocity obtained by the calculation by formula (12) at a height of $2r$; v^*_e, critical velocity transformed by dependence (13) for the 12-cm height; z, height at which the air velocity is determined; v_1, velocity at height z_1; z_0, roughness factor (height at which the velocity is equal to zero); ε_0, permittivity of vacuum; ε, relative dielectric constant of the medium; φ, angle between electrode elements; ρ, air density; η, air viscosity; τ_0, certain initial value of the time constant. Subscripts: e, electric; r, resistance; a, adhesion; p, polarized; c, centrifugal; x, component at the x axis; R, radial; 0, initial; s, stationary; f, finite; max, maximum.

REFERENCES

1. É. K. Buytner, *Dynamics of the Surface Air Layer* [in Russian], Leningrad (1978).
2. N. Fuks, *Mechanics of Aerosols* [in Russian], Moscow (1955).
3. V. N. Lazutin and V. G. Onishchenko, *Inzh.-Fiz. Zh.*, **73**, No. 6, 1135–1141 (2000).
4. S. É. Frish and A. V. Timoreva, *Course in Physics* [in Russian], Vol. 2, Moscow (1958).
5. R. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* [Russian translation], Issue 5, Moscow (1977).
6. M. I. Dolgievich, *Dust Storms and Land Reclamation Measures* [in Russian], Moscow (1978).