Erosion resistance potential as a soil erodibility characteristic based on energy approach

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Abstract. The ambiguity of existing methods encouraged researchers to search for more adequate approaches for the determination of soil erodibility. In the paper, based on the energy approach to soil erosion analysis, we have proposed a physically justified characteristic of soil erodibility as the potential of erosion resistance equal to the energy spent on the destruction and removal of a unit of soil mass in the places of its natural occurrence. The device and method of measuring the potential of erosion resistance in the field were described. The exponential character of the dependence of the erosion resistance potential on the volume moisture for light-gray and dark-gray forest soils of central region of Russia was experimentally revealed. It was shown that as the soil was moistened, the value of erosion resistance potential tended to a certain limit. Modelling of erosion processes on the basis of the proposed erosion resistance potential can allow describing erosion properties depending on the initial soil moisture and evaluating them at any time during the growing season.

1. Introduction

Soil degradation by erosion is a serious global problem and will remain so during the 21st century, especially in developing countries of the tropics and subtropics [1]. Each year about 10 million ha of cropland are lost due to soil erosion, thus reducing the cropland available for food production [2]. The relevance of the problem determines the need for further development of modeling of erosion processes and technical means of monitoring the state of soil cover for the purpose of proper use of land.

Existing empirical correlation models of erosion are not always able to explain the whole range of numerous (and sometimes contradictory) experimental and field data. The most adequate erosion model can be constructed on the basis of assessments and measurements of soil erodibility depending on soil hydrophysical characteristics [3], such as granulometric composition, structure and pedality of the soil, porosity (pore space), moisture, volume mass (density, or ratio of the sample mass to its volume).

The main characteristic used in evaluating the relief stability to the erosion, design and development of anti-erosion technologies and technical means for their implementation, is the erosion resistance of soils. The volume erosion rate is usually presented as a linear dependence on the
difference between the effective hydraulic shear stress \( \tau_e \) (Pa) and the critical shear stress \( \tau_c \) (Pa). The critical shear stress \( \tau_c \) (Pa) and the erodibility coefficient \( k_d \) \( (\text{m}^3/\text{N} \cdot \text{s}) \) – the coefficient of proportionality in the excess shear stress equation – are used as numerical characteristics of soil erodibility. The jet erosion device [4] was used to measure these values by means of determining the depth of the cavity formed in the soil by a falling jet over time. In the 2010th, the mini jet device was developed [5], and the results were compared with the results obtained at the jet erosion device. It was found satisfactory agreement in the \( k_d \) values and a significant discrepancy in the values of \( \tau_c \). The main factors affecting the measurement results were the height of the nozzle above the soil surface, the diameter of the nozzle and the initial velocity of the jet. In [6] the procedure for calibration of the jet device required to obtain consistent data was described in detail. The procedure for measuring the erodibility coefficient using the jet device was supplemented in [7] by statistical processing of the obtained data to improve the validity and accuracy of the applied technique.

The available results of \( \tau_c \) and \( k_d \) measurements using the jet device demonstrated the dependence on the computational procedure, time intervals for scour-hole depth measurements and the pressure head selection. The analysis of the results of \( \tau_c \) and \( k_d \) measurements [8] obtained by the jet device, confirmed the need to standardize field and computational procedures.

The shortcomings of determining the soil erosion resistance can be minimized based on the implementation of the energy approach to consideration of interaction of the test jet and soil particles. It was proposed [9] hydrophysical concept of soil erosion and sediment transport, based on the postulates: 1) removal and transportation of particles in the course of erosion is a kind of physical work that demands that energy be spent; 2) the removal of a particle occurs only if the flow action on the particle exceeds the particle weight and cohesion to the flow bed; 3) no new particles are removed from the points of contact of the sediment particles with the flow bed. The application of the hydrophysical concept had shown [9] its success in describing the diverse dependencies of soil erosion on numerous energy and dynamic factors determining the development of erosion. The energy approach implemented in [10] to the analysis of inconsistent results obtained by the jet erosion test (JET) and the hole erosion test (HET), eliminated the contradiction in the experimental data. The energy-based consideration allowed unifying the results of both methods and on the basis of them to carry out a unified classification of soils by erodibility.

The physical validity of the energy approach to the description of erosion processes makes promising the development of experimental methods for measuring the erodibility of soil in the field. The aim of this study is to develop the characteristic of soil erosion resistance based on the energy approach and to determine it experimentally in field conditions.

2. Materials and methods
In this study the erosion resistance of light- and dark-gray forest soils (average volume weight of 1.34 g/cm³) of oak forests of the Tsivilsky district of the Chuvash Republic (Russian Federation) were investigated. The potential of erosion resistance \( \psi \) (PER), which was the energy required for the destruction and removal of a unit of soil mass from the area of its natural occurrence, was used as a quantity characterizing the erosion resistance of soils:

\[
\psi = \frac{\Delta W}{m_s},
\]

where \( \Delta W \) was the energy expended in the destruction and removal the soil sample of the mass \( m_s \).

With this approach the question of the interaction of water flow with soil could be reduced to the evaluation or measurement of the quantities \( \Delta W \) and \( m_s \). It seemed that the experimental determination of the quantities included in the expression (1) and theoretical consideration of the problem to be solved could allow revealing the most significant interrelationships and describing the physical mechanism of erosion processes.

During the water jet interaction with soil the kinetic energy of the jet is expended on destruction of the soil structure and removal of soil particles from the emerging cavity; part of the kinetic energy is carried away by the soil particles and water flowing out of the cavity:
\[
\frac{m_w v_1^2}{2} = \Delta W + \frac{m'_w v_2^2}{2} + \frac{m_s v_s^2}{2},
\]

where \(m_w\) is the mass of water flowing out of the container under pressure; \(m'_w\) is the mass of water flowing out of the cavity; \(v_1\) is the speed of the jet before its interaction with the soil; \(v_2\) is the speed of water flowing out of the cavity; \(v_s\) is the speed of the soil particles carried away by the water flowing out of the cavity; \(\Delta W\) is the work on soil structure destruction and removal of the soil particles with the total mass of \(m_s\).

As a result of the interaction of the jet with the soil, its momentum is redistributed between the soil particles entrained by water and the water flowing out of the cavity:

\[
m_w v_1 = m_s v_s + m'_w v_2,
\]

where \(m_w v_1\) is the jet momentum before its interaction with the soil; \(m_s v_s\) is the momentum of soil particles carried away by water; \(m_w v_2\) is the momentum of water flowing out of the cavity.

Taking into account the small depth of the cavity, it can be assumed that the speeds of soil particles carried away by water and the speed of water flowing out of the cavity are the same (\(v_2 \approx v_s\)). The short-term interaction of the jet with the soil allows neglecting water absorption by the soil and, consequently, \(m_w \approx m'_w\). Under these assumptions, expressions (2) and (3) take the following form:

\[
\frac{m_w v_1^2}{2} = \Delta W + \frac{1}{2} v_2^2 (m_w + m_s),
\]

\[
m_w v_1 = (m_s + m_w) v_2.
\]

The equation for the work \(\Delta W\) is obtained by substituting the expression \(v_2\) from (4) to (5) as follows

\[
\Delta W = \frac{m_s m_w}{2(m_s + m_w)} v_1^2.
\]

Thus, according to (1), within the accepted assumptions, the potential of erosion resistance \(\psi\) (PER) can be expressed as

\[
\psi = \frac{m_w}{2(m_s + m_w)} v_1^2.
\]

The need to measure PER in the field conditions was due to the fact that the physical, mechanical and hydrophysical properties of soil in the places of its natural occurrence were somewhat different from the properties determined in laboratory conditions on monoliths and filled-up (sifted through a sieve) samples. This difference was due primarily to the drying-up of the sample during its transportation and preparation for the study. The drying-up of the sample to moisture values below the limit of field moisture capacity caused a change in the soil structure (destruction of aggregates, change in the shape of the pore space, etc.), which significantly affected the water permeability of soil. In addition, the amount and distribution of crop residues in the soil had a significant impact on PER. To justify the possibility of using the results of laboratory studies in predicting erosion processes, their comparison with field data was also required. All this caused the need to use device for measuring PER in the field.

Measurements of PER were carried out with the help of a patented device [11] developed at the Chuvash State Agricultural Academy (Russian Federation) and providing the preset volumetric rate and speed of water in the jet acting on the soil surface under study. The scheme of the device for measuring PER in the field conditions is shown in figure 1. The device consisted of a pneumatic accumulator (1), a constant pressure vessel (2), a water tank (3), a three-way regulating tap (4), an air pump (5), a pressure gauge (6), a stand (7), a nozzle (8) with an output orifice of 2 mm in diameter and connecting flexible pipeline (9). In addition, the tank (3) was equipped with a supply tube (10) and a valve (11). At the nozzle inlet, the device provided an adjustable overpressure in the range from \(1\cdot10^5\) Pa up to \(2\cdot10^5\) Pa above atmospheric pressure.

Before starting the measurement, an overpressure was generated in the pneumatic accumulator (1) by the air pump (5), whereupon the reservoir (3) was filled with water. Then, the nozzle (8) with the
stand (7) was set on the test section of soil. The required pressure $P_w$ in the tank (2) was set using the tap (4). After that, a jet of water was fed through nozzle (8) to the investigated soil section by means of the valve (11) and the connecting flexible pipeline (9). The constant value of the pressure $P_w$ in the tank (2) was maintained with help of the tap (4). The water supply to the nozzle (8) was stopped after a fixed time $t$ by closing the valve (11). Disposition of equipment in accordance with the scheme, installation of the nozzle and supply of water jet to the investigated area of the soil are given in figure 2.

![Figure 1. The scheme of the device for measuring PER in the field conditions (the explanation of the numerical designations is given in the text).](image)

The following relations were used to derive the formula for calculating PER from the results of the experiments:

$$m_s = V_s \rho_s,$$

$$m_w = V_w \rho_w = 0.25\pi d^2 v_i t \rho_w,$$

$$v_i = \mu \left(\frac{2P_w}{\rho_w}\right)^{0.5},$$

where $V_w$ is the volume of water flowing out of the container under the pressure $P_w$ during the time $t$; $d$ is the diameter of the output orifice of the nozzle; $\rho_s$ and $\rho_w$ are the bulk weight of soil and density of water, accordingly; $V_s$ is the volume of the destructed soil or the volume of the cavity; $\mu$ is the instrumental constant, determined by calibration of the device. For the device used, it was determined that $\mu = 0.533$.

The expression (4) after substitution of (5-7) and the series of transformations takes the form

$$\psi = \frac{\pi d^2 t}{\rho_w} \left[ \frac{3}{4} V_s \rho_s + \sqrt{2P_w^3} \mu \right].$$

After drying-out the cavity formed in soil was filled by the pre-calibrated bulk material from the graduated burette. Sand of ancient alluvial deposits was previously dried and sifted through a sieve with holes of 0.5 mm and further was used for the experiments as the bulk material. The volume of the cavity was determined by the volume of the spent bulk material. To determine the bulk weight of soil the samples of undisturbed addition were taken from soil surface of the same section under study. The numerical values of the PER were calculated by substituting the obtained experimental data ($V_s, \rho_s, \rho_w$) and the regime parameters ($P_w, t$) into the expression (8).
Figure 2. Measuring the potential of erosion resistance (installation of the nozzle and supply of water jet to the investigated area of soil).

PER values obtained during the preliminary testing of the proposed method under the conditions of different agricultural background showed the adequacy of the PER as a characteristic of soil erosion. PER values were 0.32, 16.62 and 4.87 J/kg for arable land, sod and land under perennial grasses correspondingly.

3. Results and discussion
The obtained values of PER for light- and dark-gray forest soils of oak forests of the Tsivilsky district of the Chuvash Republic (Russian Federation) are given in table 1 (\(M\) is the arithmetic mean; \(\sigma\) is the standard deviation).

| Date       | Dark-gray forest soils | Light-gray forest soils | Date       | Dark-gray forest soils | Light-gray forest soils |
|------------|------------------------|-------------------------|------------|------------------------|-------------------------|
|            | \(M\) (J·kg\(^{-1}\)) | \(\sigma\) (J·kg\(^{-1}\)) |            | \(M\) (J·kg\(^{-1}\)) | \(\sigma\) (J·kg\(^{-1}\)) |            | \(M\) (J·kg\(^{-1}\)) | \(\sigma\) (J·kg\(^{-1}\)) |
| 01.05.2016 | 1.44                    | 0.46                    | 07.08.2016 | 1.48                    | 0.47                    | 1.40                    | 0.46                    |
| 08.05.2016 | 0.88                    | 0.27                    | 14.08.2016 | 1.35                    | 0.41                    | 1.40                    | 0.44                    |
| 15.05.2016 | 1.20                    | 0.38                    | 21.08.2016 | 1.24                    | 0.40                    | 1.35                    | 0.41                    |
| 22.05.2016 | 1.33                    | 0.42                    | 28.08.2016 | 0.75                    | 0.25                    | 0.96                    | 0.32                    |
| 29.05.2016 | 1.51                    | 0.49                    | 04.09.2016 | 0.92                    | 0.27                    | 0.86                    | 0.27                    |
| 05.06.2016 | 1.46                    | 0.48                    | 11.09.2016 | 0.69                    | 0.21                    | 0.86                    | 0.26                    |
| 12.06.2016 | 0.77                    | 0.23                    | 18.09.2016 | 0.83                    | 0.26                    | 0.96                    | 0.30                    |
| 19.06.2016 | 0.93                    | 0.30                    | 25.09.2016 | 0.76                    | 0.24                    | 1.03                    | 0.33                    |
| 26.06.2016 | 1.25                    | 0.39                    | 02.10.2016 | 1.02                    | 0.32                    | 1.28                    | 0.40                    |
| 03.07.2016 | 0.76                    | 0.22                    | 09.10.2016 | 1.04                    | 0.32                    | 1.27                    | 0.41                    |
| 10.07.2016 | 0.93                    | 0.27                    | 16.10.2016 | 0.84                    | 0.26                    | 0.80                    | 0.26                    |
| 17.07.2016 | 1.25                    | 0.38                    | 23.10.2016 | 0.77                    | 0.23                    | 0.80                    | 0.23                    |
| 24.07.2016 | 1.36                    | 0.42                    | 30.10.2016 | 0.73                    | 0.23                    | 0.71                    | 0.21                    |
| 31.07.2016 | 1.40                    | 0.46                    | 1.34        | 0.42                    |                          |                          |

After excluding those soil characteristics which were statistically insignificant to determine PER
the set of characteristics – factors for the generalized modeling of PER was obtained. It included the porosity \(X_1\), the specific surface \(X_2\), the initial moisture \(X_3\) and the type of cultivated crop \(X_4\).

To build a linear generalized model based on the experimental data obtained, the Excel application of the Microsoft Office Suite was used. As a result of processing the data on the dynamics of PER (table 1), the LINEST function returned the array \(\{m_n; m_{n-1}; ...; m_1; b\}\) and additional regression statistics. The results of statistical processing are given in table 2.

|        | -3.65 | -0.07 | -0.05 | 4.99 |
|--------|-------|-------|-------|------|
|        | 0.92  | 0.01  | 0.02  | 0.65 |
|        | 0.74  | 0.39  | #N/A  | #N/A |
|        | 86.55 | 77    | #N/A  | #N/A |
|        | 39.22 | 11.63 | #N/A  | #N/A |

From the values of the coefficients presented in table 2, it follows that the model has the form
\[
y = 4.99 - 0.05X_1 - 0.07X_2 - 3.65X_3
\]
(12)
where \(X_1\) is the porosity, \(X_2\) is the specific surface and \(X_3\) is the initial moisture.

The coefficient of determinism \(R^2=0.74\) has a sufficiently high value for multifactor models. The F-statistic value of 86.55 indicates that the observed relationship between the dependent and independent variables is not random. The regression sum of the squares, equal to 39.22, and the residual sum of squares, equal to 11.63, confirm this conclusion.

The results of experimental data processing showed that in most cases even the linear model of PER dependence can be used for complex description of erosion resistance.

![Figure 3. Dynamics of PER values during the growing season (2016).](image)

To obtain the dependence of PER on soil moisture, the available experimental data were sorted according to the criterion accounting for the time elapsed after rain. To simulate the repeatability of PER values after precipitation, time series were used with the presence of a "seasonal" component, which was the change in the values of PER in the time interval between precipitation. The dynamics of PER during the growing season is shown in figure 3. The measurement results showed a notable decrease in the values of PER after precipitation and their restoration to the previous values as the soil dries (figure 3). By the using of conventional methods (in particular, gravimetric method of water content determination), we obtained the following power dependence of PER on the volumetric water content of soil (figure 4):
\[
\psi = 0.06 \cdot \Theta^3.
\]
(13)
The obtained dependence shows that as the soil is moistened, the value of PER tends to a certain limit.
Figure 4. Dependence of PER on the soil moisture (dark-grey forest soil).

The constructed regression model is one of the varieties of the additive time series model. Analysis of autocorrelation functions (correlograms) showed that in all cases the coefficient of autocorrelation of only the 1st order is significant (figure 4). This indicates that the seasonal component does not have a certain, clearly expressed average value, which is a period, i.e. the time interval between rains is unstable.

4. Conclusion
A characteristic feature of the soil is its spatial heterogeneity, so proper sampling and proper work with the selected samples are very important for effective testing. The article describes the method and the device for the study of soil, as well as the quantity characterizing the energy parameters of the soil erosion, destruction and run-off. The practical significance of the developed energy approach to the assessment of soil erodibility is that it is energy analysis that makes it possible to take into account the most important characteristics of the soil and to develop adequate models for predicting erosion processes.

Based on the implementation of the energy approach to the analysis of the erosion process, a physically justified characteristic of soil erodibility was proposed – the potential of erosion resistance equal to the energy spent on the destruction and removal of a unit of soil mass in the places of its natural occurrence. Application of the proposed device and method of measuring the potential of erosion resistance in the field showed consistent results. The exponential character of the dependence of the erosion resistance potential on the volume moisture for light-gray and dark-gray forest soils of central region of Russia was experimentally revealed. It was shown that as the soil was moistened, the value of erosion resistance potential tended to a certain limit.

Modelling of erosion processes on the basis of the proposed erosion resistance potential can allow describing the dynamics of erosion properties depending on the initial soil moisture and evaluating them at any time during the growing season.

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