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SOIL PHYSICS

Effect of Soil Density, Tensile Strength, and Water Infiltration on the Rupture Rate of Interaggregate Bonds

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Abstract—The effect of density of monofraction samples from the plow horizon of leached chernozem on the rupture rate of interaggregate bonds in water has been studied. The rupture rate of bonds has been determined in a hydraulic flume by alternating passive phases of 1–5 min in duration, during which the sample occurs under a nonmoving water layer, with short (15-s long) active phases with a water flow in the flume. Samples have also been tested for tensile strength and water infiltration rate. It has been shown that the rupture rate of interaggregate bonds is related by a hyperbolic law to the soil density and by an exponential law to the rate of water infiltration to the soil. The latter relationship varies within a year and, hence, can be used as reliable parameter for predicting the seasonal dynamics of soil erodibility.

Keywords: soil erosion, erodibility, interaggregate bonds, soil density, soil tensile strength, infiltration, leached chernozem, Luvic Chernozem (Pachic)

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INTRODUCTION

Separate soil properties or their combinations are conventionally used for the qualitative estimation of soil erodibility [2–4, 9, 15–17, 20, 25]. However, the developed statistic models require the quantification of soil erosion. This approach was first proposed within the framework of the universal soil loss equation [26, 27], where the erodibility of soil, which is equal to the mean soil loss from a unit sloped area under perennial fallow normalized to the mean rainfall erosion potential, is estimated from five soil parameters: humus content, soil water permeability, soil structure, and the contents of fractions 0.1–0.002 and <0.002 mm.

In physically substantiated erosion models, two parameters, rather than one parameter, are frequently determined by soil properties. In the models of Foster [19] and Larionov [13], soil properties determine the critical values of shear stress and flow velocity, as well as soil erodibility. The Mirtskhulava model [14] for the calculation of soil loss rate considers the dynamics of aggregates detached by the flow and the erosive bottom velocity, which is considered as a function of interaggregate cohesion and mass of soil aggregates. Kuznetsov [6, 7] proposed to calculate the erosive velocity from the mean weighted diameter of the aggregates detached by the flow.

Characteristics suitable for the calculation of parameters necessary for the determination of soil loss rate from erosion models increased in demand, when it was found that soil erosion parameters are subjected to seasonal variations [17, 18, 21, 22]. However, this still more complicates the procedure for the selection of parameters determining the erosion properties of soils.

We earlier showed [11] that the rupture of bonds between soil particles under water erosion is due to the penetration of water molecules into the zone of contacts between soil particles and their disturbance rather than due to the hydraulic forces of water flows, which are lower than the soil tensile strength by three orders of magnitude [23]. In this case, the bond rupture rate and, hence, the erosion intensity depend on contact area and temperature, which determines the kinetic energy of water molecules [10]. The area of contacts between soil particles, in turn, is linearly related to the soil density. This follows from approximated calculations performed under the following assumptions: (a) soil aggregates have a spherical shape and similar sizes; (b) soil material is plastic; and (c) aggregate package is hexagonal [12]. Nearing [23] believed that the soil tensile strength can also be used as an indicator of the rupture rate of interaggregate bonds and, hence, the soil erodibility.

The aim of this work was to assess the effect of soil density, tensile strength, and infiltration on the rupture rate of bonds between soil particles, which affects the erodibility of soils.

Table 1. Physicochemical properties of the plow (0- to 20-cm) horizon of leached chernozem. Physicochemical and particle-size analyses of soil were performed in the Instrumental Analytical laboratory of the Dokuchaev Soil Science Institute

OM, %	pH		TA, cmol/kg	Ca	Mg	Na	K	∑ particles <0.01 mm, %
	H_2O	KCl		cmol/kg* / % of total exchangeable bases				
5.79	6.52	5.74	2.51	32.6 / 83.2	5.06 / 12.9	0.33 / 0.8	1.20 / 3.1	59.3

(OM) mass portion of organic matter determined by the Tyurin method. (TA) total acidity determined by the Kappen method.
* Exchangeable bases determined by the Shollenberger method.

OBJECTS AND METHODS

Studies were performed on the plow (0- to 20-cm) horizon of leached chernozem (Luvic Chernozem (Pachic)) from the Volovo district of Tula oblast [1, 10, 12]. Its physicochemical properties are given in Table 1. The content of physical clay (particles <0.01 mm in effective diameter) in the soil is 59.3%. Hence, the plow horizon of the studied soil has a light clayey texture. Calcium and magnesium prevail in the soil exchange complex; their total share is 96.1% of the total exchangeable bases.

Fractions of soil aggregates 1–2 mm in size were used. A day (18–20 h on the average) before the experiments, air-dry soil samples were put in aluminum bottles; water was added in an amount equivalent to 24 wt % of the air-dry soil and uniformly distributed over the sample surface. It was found earlier that the lowest erosion rate of plow horizon in this soil was observed at an initial water content of 22–24 wt % [10].

In a series of experiments for the determination of the rupture rate of interaggregate bonds, prewetted samples of air-dry soil were packed in a container of 3.6 × 1.6 × 7.0 cm in inner size to obtain the preset soil density in the range from 1.2 to 1.5 g/cm^3 (with intervals of 0.1 g/cm^3). A block of 3 cm in height was inserted in the lower part of the container. On the day of the experiment, a wetted soil sample was spilled on a parchment sheet, mixed, and transferred by small portions into the container, where it was smoothed on the bottom and compacted with a pestle, whose lower cross section was close to that of the container. The last portion of soil was packed into an extension (with the cross section equal to that of the container) installed onto the container, and leveled. Then, a plunger, the height of which was equal to the height of the extension, was inserted into the extension and compressed with a screw press so that the surface of the soil sample was adjusted to the level of the container border. The container with soil was put into the hydraulic flume and secured with a screw. The size of the flume was reported earlier [11].

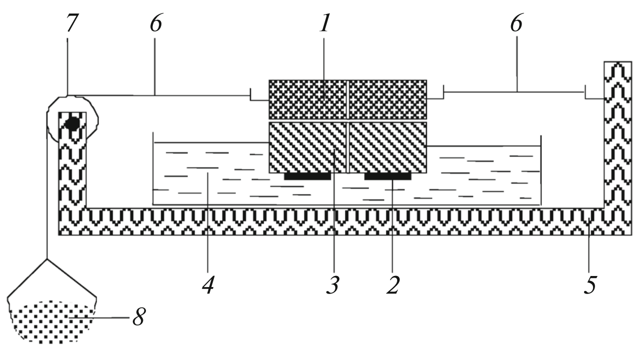

Fig. 1. Schematic diagram of the device for the determination of the tensile strength of model soil: (*1*) cylindrical container; (*2*) metal load on the float; (*3*) foam float; (*4*) box with water; (*5*) device casing; (*6*) capron thread; (*7*) block; (*8*) plastic beaker with ballast (coarse quartz sand).

In the course of the determination of the soil loss rate and, hence, the rupture of bonds between soil particles, 15-s-long active periods of the experiment, during which the particles detached from the underlying soil layer were removed by a 1-cm-deep water flow, were alternated with pauses, during which the sample occurred under a nonmoving water layer of 1 cm in depth. As shown earlier [1, 11], all soil particles disintegrated during the pause are removed for 15 s. The duration of pauses was variable: 1, 2, 3, or 5 min. Each experiment continued up to the complete erosion of the sample. Experiments were carried out in 4–8 replicates for every pause duration. Experiments without pause served as a control. A total of 120 samples were tested. All of the experiments were performed at a flow velocity of 0.95–0.97 m/s. Water temperature was maintained at 20°C. The rupture rate of interaggregate bonds was determined by dividing the sample mass by the total duration of the experiment (including the pauses and the active phases).

To reveal correlation between the rupture rates of interaggregate bonds in the soil samples and their mechanical strength, the tensile strength of soil was determined. Measurements of tensile strength for soil samples of different densities in the range from 1.2 to 1.5 g/cm^3 with intervals of 0.1 g/cm^3 were performed on an original device (Fig. 1). Samples for rupture tests were prepared analogously to those for erosion tests. The mass of soil sample was calculated from the working volume of the container and the preset soil density.

In the course of measurements, the soil sample in the cylindrical container composed of two similar tubes (the tube length was 25 mm, and the tube diameter was 18.7 mm) was installed on two floats, whose stability was ensured by steel loads, so that the container parting line coincided with the space between the floats.

After the container with soil was fixed on the floats by capron threads, sand was added by small portions as a ballast in the plastic beaker. The last sand portions before the rupture of soil in the container were added very slowly. After the soil rupture, the beaker with soil was weighed, and the rupture stress (kPa) was calculated by dividing the sand mass by the container cross section. Experiments were performed in 15 replicates.

The rate of water infiltration (seepage) in model soil samples was determined in containers in five replicates. A point gage was installed in the container with soil so that its point was 5 mm lower than the upper edge of the container, and water was added in an amount sufficient to fill the free volume of the container. A timer was started at the moment when the container was filled.

At the moment when the gage point emerged from water, the timer was stopped. The rate of water infiltration into the soil was calculated by dividing the thickness of the soil layer infiltrated with water (5 mm) by the infiltration time.

RESULTS AND DISCUSSION

The experimental determination of the tensile strength of soils with different densities showed a linear relationship between these parameters (Table 2, Fig. 2). The results of determining the rupture rate of interaggregate bonds in model soil samples with different densities (Table 3) indicate that when the total duration of active phases and pauses in the experiment increases, the rupture rate of interaggregate bonds decreases.

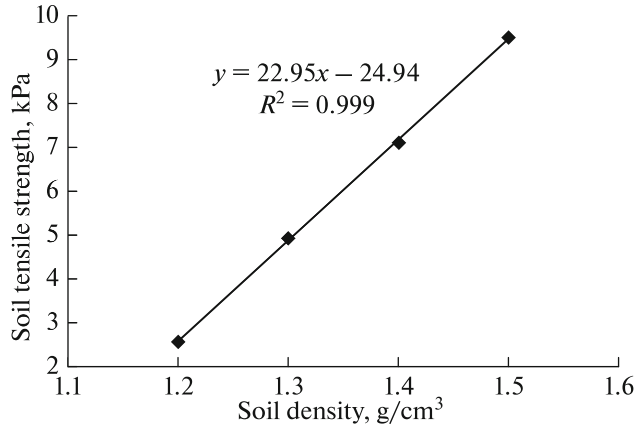

Fig. 2. Tensile strength as a function of soil density.

A close inverse exponential relationship is revealed between the rupture rate of interaggregate bonds and the density of soil (Table 4). Earlier, we showed a linear correlation between the soil density and the calculated total area of interaggregate contacts [12].

The aforesaid suggests that, along with the considered soil properties, there are other properties affecting the rupture rate of interaggregate bonds in the soil under the effect of water. These properties can include the water permeability of soils, because the rupture of interaggregate bonds requires the penetration of the wetting front, whose velocity strongly depends on the soil density. For example, 30- to 40-fold differences in the infiltration rate were noted in a sierozem compacted during the construction of terraces, as well as in the same soil of natural consistency with a density of 1.17–1.23 g/cm^3 [8]. These differences were similar in the order of magnitude to those for the rupture rate of interaggregate bonds in the soil with densities of 1.2 and 1.5 g/cm^3 (Table 3).

To verify this hypothesis, the infiltration rate of water in model soil samples was determined. Results of determining the infiltration rate of a 5-mm-thick water layer are given in Table 5, and the typical rela-

Table 2. Tensile strength (kPa) of soil samples with different densities

Statistical parameters	Soil density, g/cm^3			
	1.2	1.3	1.4	1.5
Mean (*M*)	2.58	4.94	7.14	9.50
Median (*Med*)	2.72	5.15	7.23	9.50
Standard deviation (*s*)	0.72	1.14	0.85	1.85
Maximum (max)	3.95	6.96	8.90	13.1
Minimum (min)	1.63	2.47	5.90	6.97
Variation coefficient (*Cv*, %)	27.7	23.1	11.9	19.5
Number of measurements (*n*)	15	15	15	15

Table 3. Rupture rate of interaggregate bonds in model soil samples of different densities

Number of experiments	Soil density, g/cm^3	Duration, s		Total duration of erosion and pauses, min	Mean rate of bond rupture, g/(m^2 s)	Variation coefficient, %
		pause	erosion			
5	1.2	0	–*	1.7	240.8	20.5
5	1.2	60	15	8.0	52.7	27.0
5	1.2	120	15	14.6	27.7	18.1
5	1.2	180	15	16.7	25.2	24.8
6	1.2	300	15	19.1	21.0	20.7
8	1.3	0	–*	9.7	53.9	46.0
4	1.3	60	15	15.0	24.2	9.0
5	1.3	120	15	17.0	25.5	8.2
7	1.3	180	15	26.3	14.5	13.5
7	1.3	300	15	40.1	12.8	40.4
4	1.4	0	–*	26.4	20.1	41.0
4	1.4	60	15	14.5	30.5	18.6
7	1.4	120	15	34.2	12.5	39.8
4	1.4	180	15	41.2	11.5	40.4
4	1.4	300	15	50.2	9.7	25.8
7	1.5	0	–*	65.3	10.0	24.2
5	1.5	60	15	42.9	11.9	19.0
6	1.5	120	15	49.6	11.4	47.1
5	1.5	180	15	72.7	7.0	16.0
8	1.5	300	15	97.0	5.9	39.0

* Erosion of samples without pauses.

tionship between the infiltration rate and the soil density is shown in Fig. 3. The relationship between the rupture rate of interaggregate bonds and the infiltration rate was exponential, rather than linear, with a high correlation coefficient (Table 4). This gives ground for recommending the infiltration capacity of soils as an indicator of their erosion resistance.

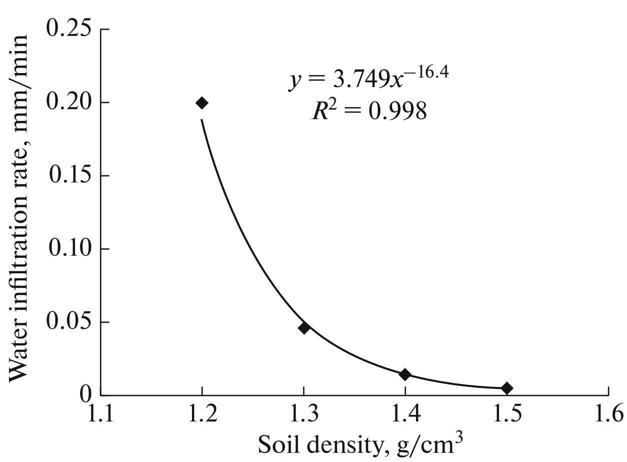

Fig. 3. Water infiltration rate as a function of soil density.

Seasonal variation is an important property of soil infiltration capacity [5, 8, 16, 17, 20, 24]; therefore, it can be used for predicting the intra-annual dynamics of soil erosion parameters.

Under contrast soil moisture conditions, such dynamics of water permeability is observed almost universally both under natural vegetation and in tilled soils [5, 8, 9, 24]. Therefore, the moisture content and wettability of soil can be used as indicators of the dynamics of soil erosion parameters. In practice, the soil water content is a more promising parameter, because the determination of soil wettability is a significantly more complex technical problem than the measurement of water content.

It should also be kept in mind that the rupture rate of interaggregate bonds in the soil depends not only on the infiltration of water into the soil, but also on the freezing, thawing, wetting, and drying of soil [7, 18].

CONCLUSIONS

The obtained results showed that the rupture rate of interaggregate bonds can be used for the determination of soil erodibility in theoretical models describing erosion processes. The rupture rate of interaggregate

Table 4. Rupture rate of interaggregate bonds (*Y*) as a function of soil density (*X*) and water infiltration rate (*Z*)

Pause duration, s	Regression equation	Determination coefficient, R^2
Soil density–bond rupture rate**		
–*	$Y = 2730^{X - 14.22}$	0.98
60	$Y = 140^{X - 5.66}$	0.78
120	$Y = 68^{X - 4.54}$	0.87
180	$Y = 66^{X - 5.48}$	0.98
300	$Y = 56^{X - 5.46}$	0.98
Infiltration–bond rupture rate***		
–*	$Y = 1191\ Z + 2.00$	0.99
60	$Y = 89\quad Z^{0.35}$	0.79
120	$Y = 46\quad Z^{0.27}$	0.85
180	$Y = 42\quad Z^{0.33}$	0.98
300	$Y = 36\quad Z^{0.33}$	0.98

* Experiments without pauses.
** Soil density (*X*) in the range 1.2–1.5 g/cm^3.
*** Water infiltration rate (*Z*) in the range 0.2–0.005 mm/min.

Table 5. Water infiltration rate into soils of different densities (initial soil water content was 24 wt % of air-dry soil)

Soil density, g/cm^3	Infiltration, mm/min
1.2	0.200
1.3	0.046
1.4	0.015
1.5	0.005

bonds correlates with such easily determinable parameters as soil density and water infiltration rate, which can also be used as reliable indicators for assessing the erodibility of soil and its seasonal dynamics.

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