ISSN 1064-2293, Eurasian Soil Science, 2018, Vol. 51, No. 2, pp. 251–254. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © G.A. Larionov, O.G. Bushueva, A.V. Gorobets, N.G. Dobrovol'skaya, Z.P. Kiryukhina, S.F. Krasnov, L.V. Kobylchenko (Kuksina), L.F. Litvin, I.I. Sudnitsyn, 2018, published in Pochvovedenie, 2018, No. 2, pp. 253–256.

Effect of Impact Angle on the Erosion Rate of Coherent Granular Soil, with a Chernozemic Soil as an Example

G. A. Larionov*, O. G. Bushueva, A. V. Gorobets, N. G. Dobrovol'skaya, Z. P. Kiryukhina, S. F. Krasnov, L. V. Kobylchenko (Kuksina), L. F. Litvin, and I. I. Sudnitsyn

Lomonosov Moscow State University, Moscow, 119991 Russia

**e-mail: larionov425@mail.ru*

Received November 30, 2016

Abstract—It has been shown in experiments in a hydraulic flume with a knee-shaped bend that the rate of soil erosion more than doubles at the flow impact angles to the channel side from 0° to 50°. At higher channel bends, the experiment could not be performed because of backwater. Results of erosion by water stream approaching the sample surface at angles between 2° and 90° are reported. It has been found that the maximum erosion rate is observed at flow impact angles of about 45°, and the minimum rate at 90°. The minimum soil erosion rate is five times lower than the maximum erosion rate. This is due to the difference in the rate of free water penetration into the upper soil layer, and the impact of the hydrodynamic pressure, which is maximum at the impact angle of 90°. The penetration of water into the interaggregate space results in the breaking of bonds between aggregates, which is the main condition for the capture of particles by the flow.

Keywords: water erosion of soils and sediments, breaking of interaggregate bonds, wedging pressure of water film

DOI: 10.1134/S1064229318020072

INTRODUCTION

Makkaveev [6] noted that the direction of streams with respect to the eroded surface (impact angle) strongly affects the erosion rate of sides and is related to the hydromonitor effect, which is maximum when the stream is perpendicular to the eroded surface. This erosion mechanism is especially important for rills on arable lands having an irregular configuration in the plane due to the original plowland topography. This statement was tested in an experiment in a hydraulic flume, in which the flow impact angle to the soil sample could be changed using inserts, the flow width remaining constant [4]. The soil sample was installed on the lateral wall of the flume facing the water flow. The angle between the flow axis and the soil sample was changed from 0° to 50° with intervals of 10°. In this range of impact angles, the erosion rate of soil samples more than doubled. At higher angles, backwater is formed in rapid streams before the channel bend, and the flow velocity decreases. Therefore, this range was not studied, although Makkaveev [6] believed that the maximum hydromonitor effect on the erosion of sides should be observed at the right impact angle of the flow.

The aim of this work was to assess the effect of the water stream impact angle in the range from 0° to 90° on the erosion rate of the plow chernozem horizon.

OBJECTS AND METHODS

Soil from the plow horizon of light clayey leached chernozem (Luvic Chernozem (Pachic)) from the Volovo district of Tula oblast was used as the initial material. Air-dry soil was sieved through a standard sieve set; portions from the fraction of 1–2 mm were taken to form samples of 1.3 g/cm^3 in density. Experiments were performed with the fraction of 1–2 mm, which prevails during dry sieving, because this fraction was used in the previous studies of soil erosion rate [5].

Soil samples were placed in weighing cups and wetted to a water content of 24 wt % of air-dry soil, which corresponded to 55% of capillary water capacity (the latter was determined for the fraction 1–2 mm by the method of capillary saturation in tubes). Soil with this water content reached the limit or near-limit consolidation [9]. After exposure for 16–18 h, the sample was transferred onto a parchment sheet, mixed thoroughly, and then put by small portions into a cartridge with a working volume of 30 × 17 × 17 mm. Each soil portion was leveled in the cartridge and preliminarily compacted to a density slightly lower than the target value (1.3 g/cm^3). After the last portion was packed into the cartridge, and the soil was compacted to the target density by turning tight the hand screw press. The soil surface was adjusted at the level of the external edge of the cartridge. The cartridge with the soil sample was installed in a container and fixed with an attachment screw. A plunger was installed in the center

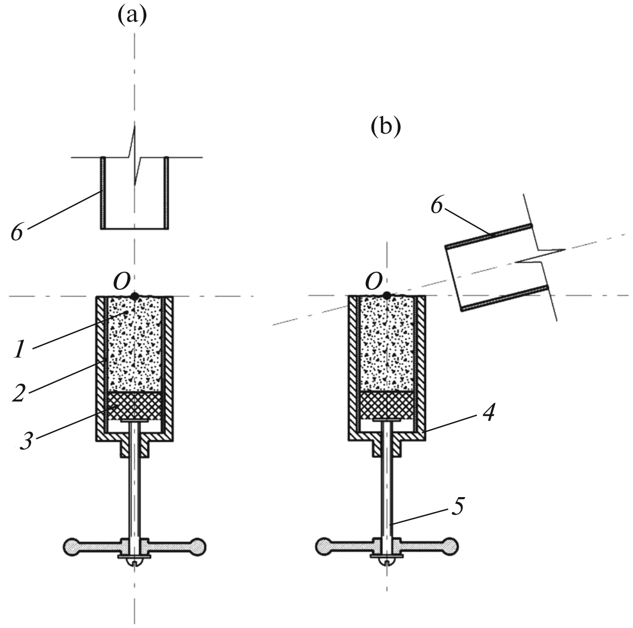

Fig. 1. Position of the flow line nozzle with respect to the soil sample surface at the (a) maximum (90°) and (b) minimum (2°) impact angles: (*1*) soil sample; (*2*) cartridge, (*3*) plunger; (*4*) cartridge case; (*5*) lead screw; (*6*) flow line nozzle; (*O*) intersection point of the water flow axis with the center of the soil sample surface.

of the container, which was moved by a lead screw (Fig. 1). The sample surface was maintained on the level of the cartridge edge throughout the experiment, which continued until the complete erosion of the sample. The beginning and the end of the experiment were fixed with a stop watch. Experiments were performed in five-eight replications for each experimental treatment. The water flow velocity from the nozzle was maintained at 1.22 m/s in all experimental treatments.

During the experiment, water temperature varied in the range from 25 to 30°C due to the absence of technical means to maintain water at room temperature. In the processing of experimental data, the soil erosion rate was reduced to the mean temperature of 27°C using an empirical relationship derived earlier [1].

Table 1. Erosion rate of soil samples (*I*) at different impact angles

Impact angle (α), degrees	*n*	*I*, g/(m^2 s)	*s*, g/(m^2 s)	*Cv*, %
2	6	113	37.0	34.4
15	5	115	20.9	34.8
30	5	336	77.1	22.9
45	6	356	92.7	26.0
60	8	175	45.2	25.8
75	5	108	38.8	36.1
90	5	68	45.9	67.6

(*n*) Number of measurements; (*s*) standard deviation; (*Cv*) coefficient of variation.

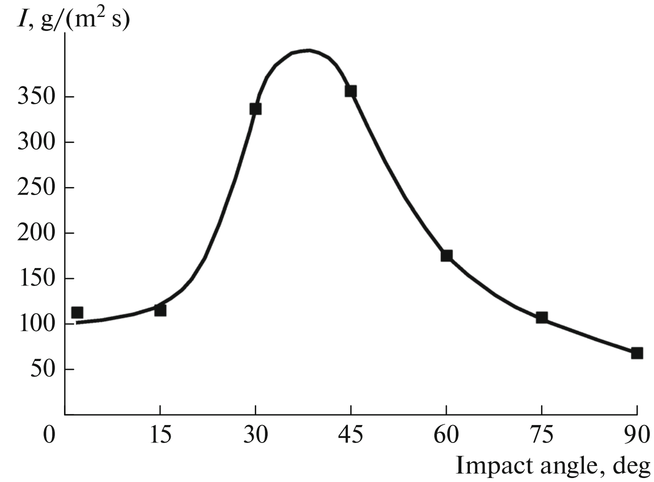

Fig. 2. Erosion rate (*I*) of chernozem as a function of impact angle.

Erosion of soil samples with a water stream was performed on a specially designed installation; the spatial position of nozzle in the installation varied from 0° to 90°.

The impact angle was set by changing the inclination of the nozzle. In the first experimental treatment, the angle was 2° to avoid the rebound of water flow from the soil surface. Later on, the impact angle was changed up to 90° with intervals of 15°.

The erosion rate was calculated by dividing the sample weight by the erosion time in seconds and reduced to 1 m^2.

RESULTS AND DISCUSSION

The results of study are given in Table 1. Statistical processing of data shows that the variability of sample erosion rate remains within the same limits as in our previous studies. This can be the assurance that the erosion mechanism in this experiment is the same as in the earlier studies [1, 3]. It is noteworthy that the maximum erosion rate is observed at an impact angle of about 45° and decreases with either increasing or decreasing angle. The minimum soil erosion rate, which is five times lower than the maximum erosion rate, is observed at an impact angle of 90°.

It was shown earlier [2] that the breaking of bonds between soil particles in the absence of external mechanical stress and in the presence of free pore water is due to the wedging impact of diffuse water films formed during the hydration of double electrical layer (Gouy–Chapman layer). During the diffusion of water into this film, the thickness of the latter increases, tending to infinity. Therefore, the particles

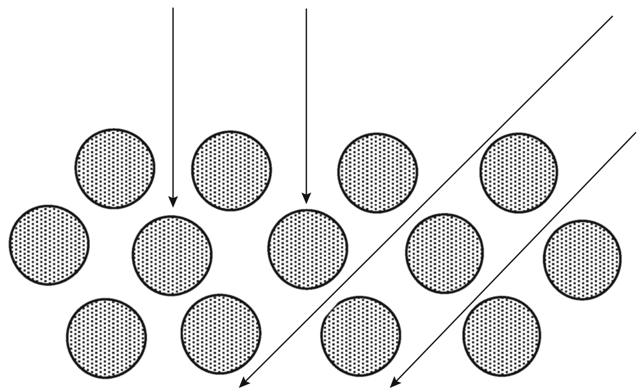

Fig. 3. Inertial movement of water in the soil at impact angles of 45° and 90°.

of the outer layer move from the bulk mass to a distance a priori longer than the acting radius of intermolecular forces (<50 nm) [7]. They can be considered as particles unbound to the resting soil mass and freely lying on the soil surface. In this case, the flow the tangential stress of which at the contact with the soil is lower than the tensile strength of soil [8] by three orders of magnitude is capable of capturing particles freely lying on the surface of the test sample. Thus, the scouring velocity for a cohesive granular soil at the constant flow velocity and other conditions equal depends on the rupture rate of interaggregate bonds in the surface soil layer, which is not subjected to the pressure of overlying soil material, under the impact of free pore water.

An experiment proof for this hypothesis can be the almost linear relationship between the scouring velocity of monogranular soil samples of different densities and the filtration rate of water through samples [5]. The rate and volume of water input from the jet into the surface soil layer depends on its impact angle. The optimum conditions for water input from the jet into the granular soil are created at an impact angle of 45° (Fig. 3). In this case, hydrodynamic pressure facilitates the movement of water deep into soil. At an impact angle of 90°, the water jet branches falling into the gap between particles of the upper layer loose the dynamic pressure already in the second layer of soil particles. Therefore, water penetrates into soil samples more slowly and less deeply during erosion; hence, interaggregate bonds break more slowly. Thus, water jest cannot detach soil particles until these bonds are not broken. This is one of the reasons for the minimum scouring velocity of samples at an impact angle of 90° in the entire range of angles.

Another reason is related to the hydrodynamic pressure of water jet to the sample surface. It was found in earlier experimental studies that hydrostatic pressure strongly decreases the erosion rate of cohesive soil samples, all other conditions being equal. This is due to the presence of water layer adsorbed on the surface of clay particles.

The adsorption of water molecules is based on the phenomenon of epitasis, which involves the adaptation of water molecules to sorption sites on the surface of mineral particles due to the deformation of hydrogen bonds with the formation of structured water film, the properties of which significantly differ from those of free water. Water in the adsorption film does not transfer hydrostatic pressure; it has an increased viscosity (3–5 times) compared to free water and it has no suspend ability [7]. The first property ensures the transfer of hydrostatic pressure at the level of clayey soil particles. The second property decelerates the diffusion of free pore water into the interaggregate space. Both these factors slow the formation of wedging water film between particles in the double electric layer. All this decreases the breaking rate of interaggregate bonds in the clayey soil; the detachment of soil particles by the water flow is impossible without breaking their cohesion, because the tangential stresses on the soil surface created by the water flow are lower than the cohesion force between soil particles by three orders of magnitude [8]. In our case, at an impact angle of 90°, hydrostatic pressure is substituted by hydrodynamic pressure.

At low impact angles (2°–15°), hydrodynamic pressure can be ignored. In this case, the infiltration of water into the sample is due to gravity and capillary forces, which are manifested at any impact angles; however, its contribution to the breaking of interaggregate bonds and the soil erosion is apparently low because of the relatively high water content in the model samples. To assess the role of capillary forces in the erosion of cohesive soils by a water stream at different impact angles, experiments at the low initial water content of samples should be performed.

CONCLUSIONS

The impact angle between the water stream and the surface of coherent soil strongly affects the erosion rate. The maximum erosion rate of coherent soil is observed at impact angles of about 45°, and the minimum rate at 90°. The maximum and minimum erosion rates are more than 5 times different. This effect of the impact angle on the erosion rate of cohesive soils is related to the breaking mechanism of interaggregate bonds at the periphery of cohesive soils, where the dynamic equilibrium is disturbed and interaggregate bonds between clay particles are broken in the presence of free pore water, which is the initial erosion stage of cohesive soils. The rate of water infiltration into the surface layer of cohesive soil depends on the impact angle of water stream to the sample surface.

ACKNOWLEDGMENTS

The work was performed within the framework of the research plan of the Makkaveev Research Laboratory of Soil Erosion and Channel Processes and was supported in part by the Russian Foundation for Basic Research (project no. 16-05-00474a).

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Translated by K. Pankratova