========================== SOIL EROSION ==========================

Effect of Gravity on the Erosion of Model Samples

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Abstract—The article is devoted to the theoretical analysis and experimental investigation of the bottom and lateral erosion in shallow flows on slopes. The analysis of the ratio between the forces detaching and retaining a soil particle has showed that the erosion of the bed sidewall exceeds manifold the erosion of the bottom at the flow velocity close to the threshold value. When the flow velocity increases, the differences in the rate of erosion between the bottom and the sidewalls of the rill are leveled. The rate of sidewall erosion strongly depends on the slope of rill sides. The experimental studies of the effect of the sample surface inclination have completely confirmed the theoretical conclusions. It should be kept in mind that the lateral erosion under natural conditions is also limited by the laws of hydraulics. When the rill bed is widened due to the lateral erosion, the flow width increases and, hence, its velocity decreases to below the threshold value, which stops the erosion of the bed.

INTRODUCTION

In the experimental studies of water erosion, the test soil sample is usually placed on the bottom of a hydraulic flume. The results thus obtained give an indication of depth erosion. However, the most common erosion type (rill erosion) involves not only the downcutting of rill beds, but also their enlargement due to the so-called lateral erosion: erosion of rill sides. Almost no attention was given to the physical simulation of lateral erosion. Our work was devoted to lateral erosion under specific conditions of the oblique impact of a stream on a rill wall. The approach of the stream to the rill wall at an acute angle results in a hydro-monitoring effect, which was first reported by Makkaveev [7]. Therefore, the rate of soil erosion on the concave banks of rills increases proportionally to the cube of the sine of the approach angle of the stream to the bank [1]. However, even in the absence of rill bends, there are grounds for believing that the erosion of the sides can proceed more rapidly than that of the bottom, because the stream capturing a particle from the bottom should work against its gravity, while on the rill side, the weight of the particle contributes to its detachment. This fact should be taken into consideration, which became obvious after understanding the mechanism for the rupture of bonds between soil particles during erosion. As was found earlier, the hydration of soil results in the appearance of orientation-dependent repulsion forces between the soil particles and, hence, the disturbance of bonds between them,

so that the capture of particles by the stream includes only their lifting and propulsion [3].

The aim of this work was the theoretical analysis of lateral erosion and the experimental study of the erosion of model soil samples whose surface occurs at different angles with respect to the horizon.

Let us consider the approach proposed by Lelyavskii [6] for assessing the erosion of river banks. According to this approach, the erosion of a low bank on a straight segment is a linear function of shear stress

$$\tau = \rho g H I, \qquad (1)$$

where τ is the shear stress, ρ is the water density, g is the gravity acceleration, H is the depth, and I is the inclination of the surface. It follows that the sides of flow beds should be vertical and even overhanging; however, the river sides are usually composed by incoherent or low-coherent sands, which crumble and form sides with the gradient equal to the angle of internal friction of water-saturated soil. In this case, the rate of bottom erosion should exceed the rate of lateral erosion. It is seen that the Lelyavskii's approach [6] does not consider the fact that the flow capturing particles from the bottom should work against gravity, while the capture of particles from the side is favored by gravity (or its constituent in the case of a nonvertical side).

Mirtskhulava also gave attention to lateral erosion, although on the level of macrochannels. Without detailed analysis of lateral erosion, he believed that the cross-section area of the stabilized flow bed

Table 1. Dependence of erosion rate on the flow velocity and the orientation of soil with respect to the horizon (calculation from Eq. (3))

Inclination, degrees	Erosion rate at flow velocity, m/s		
	0.525	0.96	2.00
0	1.00	1.00	1.00
45	868	1.13	1.02
90	2944	1.44	1.08
135	5020	1.75	1.13
180	5881	1.88	1.15

should be determined from the morphological relationships with consideration for the physicotechnical parameters of the resistance of sediments composing the stream bed [8].

Let us consider another approach to the effect of particle gravity on the erosion of the sidewall of the flow. We define the forces (F) acting on the particle in the flow as follows:

$$F = \rho_w k_{if} v^2 d^2 - \cos\alpha (\rho_p - \rho_w) \mu g d^3, \qquad (2)$$

where ρ_w is the density of water, k_{lf} is the generalized drag and lift coefficient, v is the flow velocity, d is the diameter of soil particle, α is the inclination angle of the sample surface, ρ_p is the density of soil particle, μ is the coefficient of sliding friction, and g is the gravity acceleration. Dividing the both sides of Eq. (2) by the first term in its right side, we obtain the following dimensionless relationship:

$$\frac{F}{\rho_w k_{if} v^2 d^2} = 1 - \frac{\cos\alpha (\rho_p - \rho_w) \mu g d}{\rho_w k_{if} v^2}, \qquad (3)$$

in the left side of which the numerator is a constant value at any orientation of the sample surface with respect to the horizon, if the flow velocity and the soil

particle size remain unchanged. It follows from the hydrophysical erosion model [2, 5] that the erosion is proportional to the cubic flow velocity. In the case of constant flow velocity, the force ratio gives an indication of the effect of the sample surface inclination on the erosion rate.

The numerical analysis of Eq. (3) (Table 1) shows that the higher the flow velocity, the lower the effect of the sample surface inclination on soil erosion. When the flow velocity decreases, the differences in the erosion rate of soil samples with different surface inclination angles increase. They obviously will be maximum at the flow velocities close to the threshold values, at which the flow bottom is not eroded, while on the side walls the gravity favors the detachment of soil particles.

MATERIAL AND PROCEDURE OF THE STUDY

The erosion of model soil samples was studied in a rectangular tube with a cross-section of 19.5×29.9 mm and a length of 1020 mm made of Plexiglas 12 mm thick. The tube ends are joined to short steel nozzles through fitting pieces with a rectangular cross-section corresponding to that of the tube on one end and a round cross-section 20 mm in diameter for the connection to the nozzles on the other end. One nozzle is connected by a flexible pressure pipe with a valve to a pump, and the other nozzle is connected by a pipe with a valve to a water reservoir, from which water returns through a tissue filter to the pump. On a wide side of the tube, a window of 20×20 mm is made at 650 mm from the tube end for a cartridge with soil of 70 cm in length (Fig. 1). A thick-wall square Plexiglas duct is installed in the window to hold the cartridge, which is fixed by an attachment screw fitted in the threaded hole. Four studs are installed in the corners of the duct walls to fix the square plate with a square hole for the cartridge. The plate tightens several layers of rubber seals, preventing water leaks through the gaps between the cartridge and the duck walls. A plunger to press the soil out of the cartridge as far as it is eroded is also installed on the plate.

The object of study was clay loamy chernozem from the Volovo district of Tula oblast. The fractions of 1−2 mm obtained by sieving the dry soil through a standard sieve set were used for the preparation of model samples. The soil samples were placed in metal cups and wetted to 24% water 12−16 h before the beginning of the experiment.

Immediately before the experiment, the wetted sample was poured from the cup onto a parchment sheet, mixed, and transferred in small portions in the cartridge with an insert in its lower part to transfer the pressure from the lead screw to the soil sample. The insert was covered with parchment to facilitate the detection of the end of the experiment. Each soil sample was spread over the cartridge cross-section and compacted with a metal pestle tightly fitting into the cartridge. Before the packing of the last soil portion,
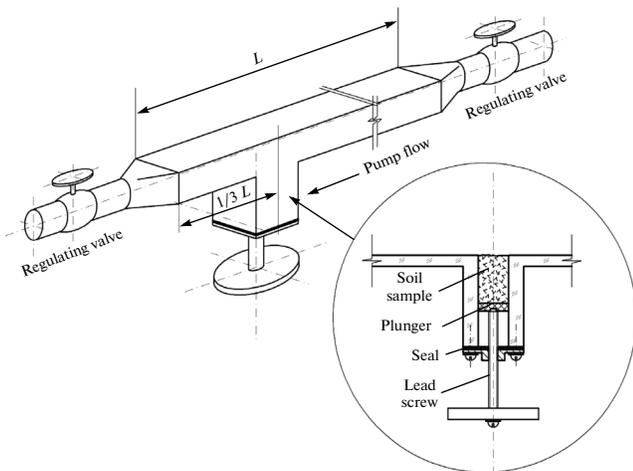
Fig. 1. Schematic diagram of hydraulic tube.

Table 2. Mean values (*M*), standard deviations (δ and variation coefficients (*C*v) for the soil erosion rate (experimental data and those normalized to 20°C and a flow velocity of 0.96 m/s)

Soil surface inclination, degrees	Water flow velocity, m/s	Soil erosion rate			
		experimental			normalized
		M, g/s per m^2	σ, g/s per m^2	Cv, %	M, g/s per m^2
0	0.95	87.5	14.5	16.6	82.0
45	0.96	103.7	8.4	8.1	105.8
90	0.96	133.6	44.2	33.1	133.2
135	0.96	137.2	33.3	24.3	134.5
180	0.97	143.7	40.5	28.2	148.6

the cartridge was put in the screw press chamber, and an extension was placed on the cartridge, wherein the resting soil portion was poured, flattened, and compacted with the pestle. Another insert, whose height was exactly equal to that of the extension, was then inserted in the extension, and the press was screwed down. Thus, the sample surface became located in the same plane with the cartridge edge.

The cartridge with the sample thus prepared was placed in the duct so that the sample surface was in the plane of the inner wall of the tube. The cartridge was then fixed with the clamping screw; three rubber seals were put on it; the square plate with the hole for the cartridge was installed, and the nuts were drawn to ensure the tight connection of the cartridge with the duct. Before the beginning of the experiment, the water rate ensuring a flow velocity of 0.95–0.97 m/s was adjusted with the outlet valve of the pump. All the experiments were performed at this flow velocity. The average flow velocity could not be maintained in a narrower range for technical reasons. The water rate was measured with a water meter and a film camera.

The rate of soil erosion depends on the water temperature [3]; therefore, the latter was maintained in the range of 19 to 23°C throughout the experiment by adding warm or cold water, respectively, to the reservoir.

The erosion rate of soil samples was determined for five different angles of the sample surface with respect to the longitudinal flume axis: 0, 45, 90, 135, and 180 degrees. The experiments were performed in 5 replicates for each experimental treatment. The time of complete erosion of the model soil sample was determined using a stopwatch timer: the appearance moment of the light-colored parchment on the plunger pushing the sample from the cartridge was considered to be the end of the experiment. All the experiments were carried out on model soil samples with a density of 1.3 g/cm^3.

RESULTS AND DISCUSSION

The results of the experiments indicate an important role of the angle of the sample surface with respect to the horizon (Table 2). The samples whose surface lies in the horizontal plane are eroded more slowly than the samples with the opposite location of the eroded surface by more than 1.5 times. For a more correct estimation of the effect of the studied factor on the erosion rate, the experimental data should be recalculated for the same water temperature and the same flow velocity, because these parameters could not be maintained within the selected range throughout the experiments. For example, the water temperature fell to 19°C in cold days and rose to 23°C during separate experiments in warm days. As was noted above, constant flow velocity also could not be maintained in all experimental treatments for technical reasons; moreover, it sometimes varied within the treatments. Therefore, the experimental values of soil erosion obtained in all experimental treatments were normalized to a temperature of 20°C and a flow velocity of 0.96 m/s.

The normalization to the standard temperature was based on our early results obtained in the study of the effect of water temperature and water content of the soil used for the preparation of model samples [3]. According to these data, when the temperature changes by 1 degree in the range from 17 to 23°C, the relative gradient of soil erosion rate is 0.074. The temperature deviation from the selected value (20°C) was multiplied by the gradient; the obtained value was multiplied by the experimental erosion rate, and the result was algebraically summed with the above value.

To correct the data for the flow velocity, the mean values of erodibility in the experimental treatments were calculated by the division of the erosion rate (g/(cm m^2)) by the cube of the mean flow velocity, as follows from the hydrophysical erosion model [5]. The erosion rate normalized to the flow velocity averaged for all experimental treatments (0.96 m/s) was calculated as the product of the erodibility averaged over the
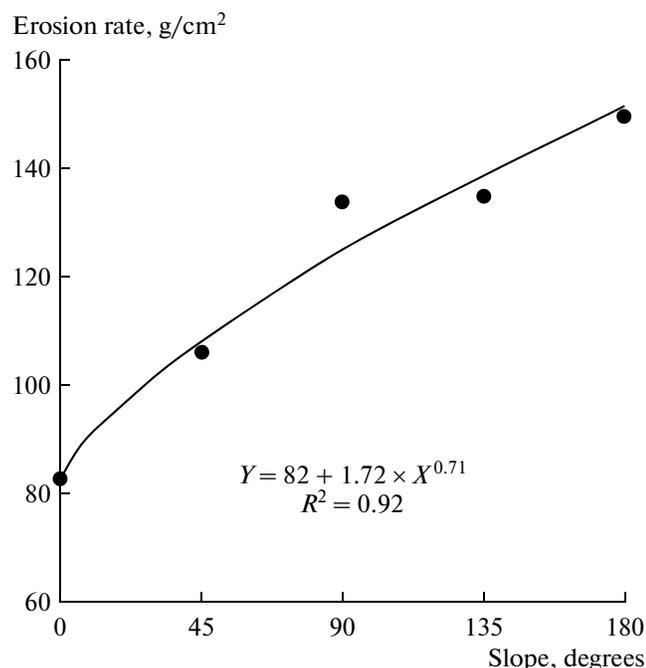
Erosion rate, g/cm^2

$$Y = 82 + 1.72 \times X^{0.71}$$
$$R^2 = 0.92$$

Fig. 2. Soil erosion rate as a function of soil surface inclination.

treatments by the cube of the water flow velocity averaged over the treatments. The experimental data normalized to the water temperature of 20°C and the same flow velocity are given in Table 2.

The experimental results showed a close correlation between the erosion rate and the sample surface angle to the horizon. It can be described by an exponential function (Fig. 2).

Another ratio between the lateral and bottom erosion is obviously possible under natural conditions because of the effect of the attendant factors. For example, the increase of soil density down the profile, which is accompanied by a decrease in erodibility, can significantly reduce the rate of depth erosion and favor the development of lateral erosion. The content of suspended sediments in the flow also can decelerate the deep erosion and activate the lateral erosion, because the suspended sediments clog the interaggregate pores and decrease the erodibility of the soil covering the flow bottom. The presence of the sand fraction of bed load sediments in the flow, on the contrary, increases the rate of bottom erosion because of the corroding effect of sand particles and reduces the relative contribution of lateral erosion to the total soil loss [4].

All the aforesaid refers to the erosion normalized to the unit eroded surface. Under real conditions, the ratio between the surfaces of bottom and lateral erosion can be different. The lateral erosion itself increases the surface of rill bottoms and, hence, decreases its own contribution to the total soil loss. However, if the water rate remains unchanged, the

flow depth decreases; hence, the mean flow velocity decreases proportionally to the square root of the flow depth, which largely favors the reduction of soil loss because of rill erosion. At the same time, the bottom erosion deepens the rill bed, which increases the active area of lateral erosion and, hence, its contribution to the total soil loss; when the water level becomes lower than the soil surface, the soil loss also increases due to the caving of the hollowed rill sides.

Thus, the experimental studies show that the lateral erosion per unit surface exceeds the bottom erosion, because the gravity favors the lateral erosion. At the low flow velocities comparable to the threshold values, the lateral erosion is significantly higher than the bottom erosion; when the flow velocity increases, the difference decreases but remains significant in the range of real flow velocities on slopes.

It should be kept in mind that, under real conditions, the width of rill increases because of erosion of the border, which results in an increase of the flow depth at the constant flow rate. Consequently, the flow rate decreases down to the threshold value, first for the bottom erosion and then for the lateral erosion. Thus, the ratio between the bottom and lateral erosion under natural conditions also depends on the hydraulic parameters of the flow.

CONCLUSIONS

Experimental study and theoretical analysis showed that (a) the erosion rate of the side walls of the rill bed increases proportionally to their slope, and (b) the contribution of the lateral erosion on the straight segments of rill beds to the total soil loss from the plowed slopes is inversely related to the flow velocity. At the flow velocities comparable to the threshold value, the soil loss is mainly due to the lateral erosion. If the flow velocity exceeds the threshold value by many times, the relative contribution of lateral erosion to the total soil loss is reduced. The actual ratio between the lateral and bottom erosion is probably significantly more complex because of the effect of other bed-formation factors. Nonetheless, the obtained relationships for the development of rill erosion, which cause major soil losses from the arable lands, should be taken into consideration in the development of physically based erosion models.

REFERENCES

1. G. A. Larionov, V. M. Gendugov, N. G. Dobrovol'skaya, Z. P. Kiryukhina, and L. F. Litvin, "Mecha-

nisms of lateral erosion in rills on slopes," Eurasian Soil Sci. **41** (3), 294−301 (2008).

2. G. A. Larionov, *Erosion and Deflation of Soils: General Regularities and Quantitative Assessment* (Izd. Mosk. Gos. Univ., Moscow, 1993) [in Russian].

3. G. A. Larionov, O. G. Bushueva, N. G. Dobrovol'skaya, Z. P. Kiryukhina, S. F. Krasnov, and L. F. Litvin, "Effect of the water temperature and soil moisture on the erodibility of chernozem samples: a model experiment," Eurasian Soil Sci. **47** (7), 734−739 (2014).

4. G. A. Larionov, N. G. Dobrovol'skaya, Z. P. Kiryukhina, and L. F. Litvin, "Effect of the hardness of streambed sediments on soil erosion," Eurasian Soil Sci. **38** (4), 437−441 (2005).

5. G. A. Larionov and S. F. Krasnov, "Probabilistic model of soil and cohesive ground erosion," Eurasian Soil Sci. **33** (2), 205−211 (2000).

6. S. I. Lelyavskii, *Introduction to River Hydraulics* (Gidrometeoizdat, Moscow, 1961) [in Russian].

7. N. I. Makkaveev, *Runoff and Channel Processes* (Izd. Mosk. Gos. Univ., Moscow, 1971) [in Russian].

8. Ts. E. Mirtskhulava, *Engineering Methods of Calculation and Prediction of Water Erosion* (Kolos, Moscow, 1970) [in Russian].

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