DESTRUCTION OF THE BONDS BETWEEN SOIL PARTICLES IN THE PROCESS OF WATER EROSION

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It is known that tensile strength of soil samples is by three orders of magnitude greater than the shear stresses on the bottom of slope streams responsible for the detachment and transport of soil particles by water current. C.E. Mirtskhulava believed that detachment of soil particles by water current occurs due to the fatigue destruction of bonds between soil particles.Taking this into account, tensile strength is lower by two orders of magnitude. M.A. Nearing had an opinion that detachment of soil particles occurs in the points of separation of vortices from the bottom of the stream, where the shear stress is by two orders of magnitude higher than the average. These approaches did not explain overcoming by slope streams of the cohesion forces between soil particles. Studies of the influence of water temperature on the washout rate of model samples have shown strong correlation between the two, which is close to the Van't Hoff's rule. This means that destruction of bonds between soil particles is probably the result of interaction between the soil solid phase and water molecules. Experiments have shown that destruction of bonds between soil particles in the sample of chernozem mono-aggregate soil occurs under a layer of still water. Upon the start of the water flow, particles that lost bond with the rest of the soil body immediately break away. The number of particles with disrupted bonds grows with the duration of the sample exposure to still water, although with some flattening. Experiments confirm the validity of the hypothesis of non-hydraulic nature of forces that disrupt inter-aggregate bonds during water erosion.

Keywords: mechanism of erosion; inter-aggregate bonds; soil tensile strength; Van't Hoff's rule; disruption of inter-aggregate bonds.

The resistance of soil particles to detachment by water flow, is, as a rule, much higher than forces of hydraulic origin, to which the bed of the stream as a whole, as well as composing it soil particles are exposed. Therefore, C.E. Mirtskhulava in proposed back in 1970 erosion equation used the idea of fatigue destruction of bonds between soil particles under the influence of dynamic loads experienced by the bed of the stream due to local velocity pulsation of water flow. Research of fatigue strength of soils and their rate of washout showed the similarity of these processes and therefore, by analogy with the equation describing the curve of the fatigue strength, the number of stress cycles (N) before the moment of separation of particles can presented in the form

$$N = \frac{188000}{\frac{v_{\Delta_x}^2}{v_{\Delta perm}^2} - 1}, \qquad (1)$$

where $v_{\Delta x}$ and $v_{\Delta perm}$ are respectively bottom speed at the height of the roughness level at a distance x from the beginning of the stream and permissible (noneroding) speed. The ratio of the squares of these velocities is equivalent to the strength at the initial moment applied on the soil particle and at the time of it detachment by water flow. From equation (1), knowing the frequency of the pulsation velocity in the flow, it is easy to determine the number of particles detached by flow per time unit and extending this number per unit area, to obtain the equation of soil particles in the form

$$q = 0.0000064\, \gamma \omega d^2 \left(\frac{v_{\Delta x}^2}{v_{\Delta perm}^2} - 1 \right), \qquad (2)$$

Where q is soil loss per unit area, d is the diameter of detachted particle, γ is the density of the particle, ω is the frequency of the velocity pulsation in the flow. Others are previous designations. Later C.E. Mirtskhulava (1970) assumed the frequency of pulsations in slope flows as a constant value. Allowable speed according to his point of view is a function of the square root of the weight of soil particles in the water and the fatigue strength of the soil (C_y). The latter is determined by the dependence:

$$C_y = 0.035C, \qquad (3)$$

M.A. Nearing et al. (1991) has also paid much attention to this issue. Study of the tensile strength of 33 different soils of the USA showed that this property of all soils fall within the range from 0.9 to 3.2 kPa. Analysing the results of his research of mono-aggregate soil samples, showed that their tensile strength is within the above range, three orders of magnitude greater than the shear stresses on the bottom of the shallow streams and however, the soil samples were successfully eroded. To explain this paradox M.A. Nearing (1991) used the results of studies of Grass (1970), according to which the shear stresses at the points of the bottom area, where vortex disturbances separate from bottom (burst event), are two orders of magnitude higher than the average magnitude of the tangential stresses at the bottom of the stream, assuming that it is at these points soil particles are detached. Because the separation of the vortices from the bottom of the stream is of stochastic nature, the equation of the detachment of soil particles includes a probabilistic block. However, this solution seems to be not quite correct, because the shear stress at the point of separation of the vortex, though two orders of magnitude higher than the average shear stress, still is an order of magnitude lower than the tensile strength of soil.

However, the solution to this problem proposed by C.E. Mirtskhulava, also cannot be considered perfect. If we assume that the adhesion of the soil, determined by the spherical stamp intrusion into the soil at full water saturation (Tsitovich, 1963) is equivalent to the soil tensile strength, as it C.E. Mirtskhulava believes (1966), the fatigue tensile strength, which is calculated according to the above formula (3) is an order of magnitude greater than the maximum value of the tangential stress in the places of vortices separation. Thus the solution to the problem of separation of particles of cohesive soils by slope water flows from the position of the bonds destruction between soil particles is not quite correct.

There are other facts that contradict the idea of a hydraulic nature of the forces responsible for the destruction of the bonds between soil particles. According to many models of erosion (Foster, 1982; Rose, 1985 and others) the intensity of soil particles detachment is linear depending on the value of active erosion factor. In the hydro-physical model of soil erosion (Larionov, Krasnov, 2000) the intensity of erosion is proportional to the cube of the flow velocity if it exceeds a threshold value by 1.5–2 fold. This suggestion has been proved experimentally. Soil samples of 1.2 g/cm^3 density were tested in the fairly wide range of speeds. Experiments have shown positive results (Fig. 1). The linear relationship between the soil washout and the cube of the flow velocity has been obtained for the flow velocity 1.5 times higher than the critical value.

However, in the study of samples of higher density, it was found that the dependence between the rate of erosion of the samples and the cube of the flow velocity has a distinct turning-point (Fig. 2).

It turned out that the intensity of the detachment of soil particles is not proportional to the cube of the average flow velocity over the entire investigated range of speeds. At certain value of speed the trend line on the graph flattens. The first attempt to explain this phenomenon was based on the fatigue approach to the destruction of bonds between soil particles. As known, in the process of fatigue destruction multiple oppositely directed loads leads to cracks formation in the points of

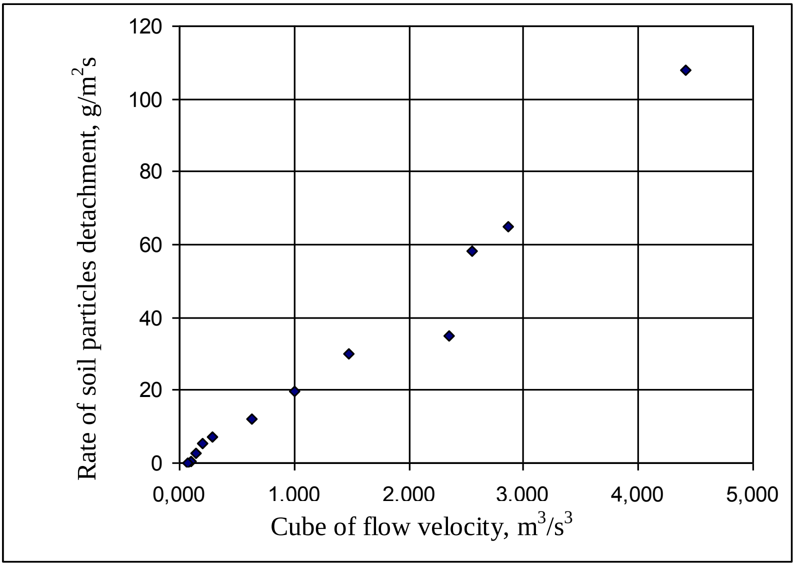

Fig. 1. Dependence of the intensity of the erosion model sample soil density of 1.2 g/cm^3 from the cube of the flow velocity.

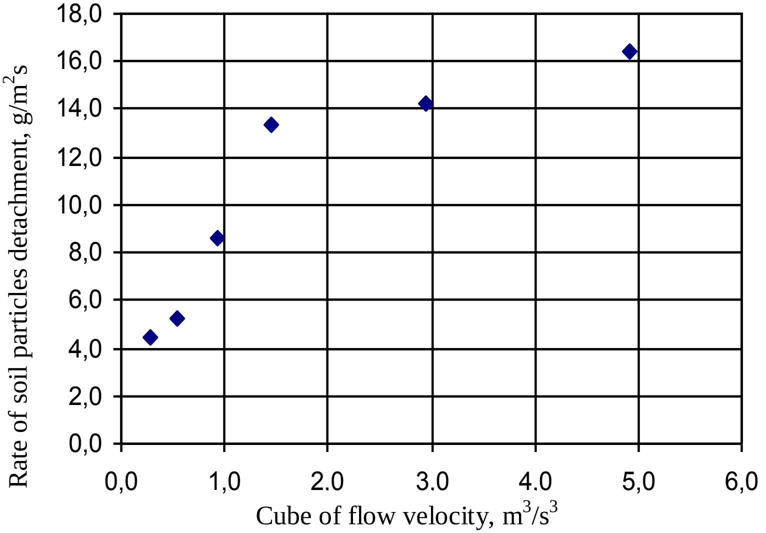

Fig. 2. Dependence of the intensity of the erosion model sample soil density of 1.5 g/cm^3 from the cube of the flow velocity.

structural defect, where over time, destruction of the material occurs. In case of unidirectional cyclic loading, which is typical for particles on the stream bed, reciprocating movement in the material can take place only in the presence of the material elastic properties. Assuming that the soil particles possess elasticity, we can suppose that the separation of the particles by the flow of water occurs as a result of repeated cycles of reciprocating motion, which is possible only in the case when the minimum value of the load of the hydraulic nature will be less than the force of elasticity of the particles. With the rise in the minimum loads the amplitude of the reciprocating movement will be reduced, which can cause a relative slowdown of separation of particles with increasing flow rate. With unlimited growth of flow velocity minimum pulse load will obviously exceed the elastic force of the soil particles, resulting in the stop of reciprocating motion of the oscillations of the particles and halting their separation. However, the erosion of model soil samples did not stop even at speeds above 7 m/s. Thus, the idea of destruction of bonds between soil particles due to fatigue does not work in this case too.

A chance pointed in what direction to look for the solution of the problem of breaking bonds between particles during erosion by water flow, shear stresses on the bottom of which is three orders of magnitude less than the soil tensile strength. One day, while conducting a series of experiments at a constant flow rate, water temperature rose as a result of operation of the pump from 13 to 25ºC and the speed of erosion of the soil samples increased. In connection with this, the rate of erosion of the samples was studied in the wide range of water temperature (from 0 to 30ºC) with increments of 5ºC (Fig. 3). It turned out that with increasing water temperature by 10ºC the rate of erosion increased by 1.5–1.6 times that almost fits into the framework of Van’t-Hoff‘s rule, which reflects the influence of the velocity of the molecules of the reacting substances on frequency and intensity of their mutual impacts and thus on the reaction rate. Consequently, the destruction of the bonds between soil particles is not the result of actions of hydraulic forces but of the kinetic energy of the water molecules.

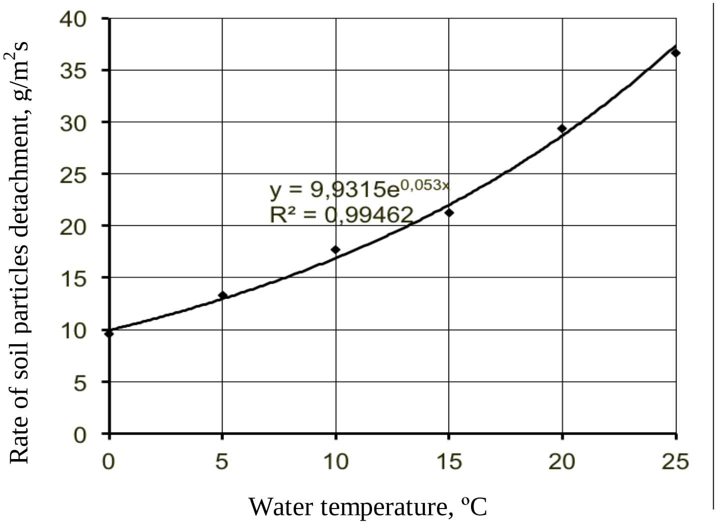

Fig. 3. Effect of water temperature on the rate of soil particles detachment.

In this respect we conducted exploratory research in order to 1) develop of methods for determination the rate of bond destruction between soil particles; 2) search for factors of destruction inter aggregate bonds in soil samples.

The destruction of the bonds between soil particles can’t be visually observed. Mechanical separation of particles that lost their connection with the soil mass is also impossible. The most optimal is using of the stream power to remove particles lost their connection with the underlying aggregates from the surface of the sample. To assess the role of water as a substance which causes the disruption of bonds between soil particles the following method was applied. Water was supplied to a tray with pauses, during which the water flow was absent, but the soil sample was under the 1 cm water layer. Experiment started by a pause. In 1–2 cm below the sample impermeable barrage was placed with the height of a little more than 1 cm and water was poured in amount to provide depth of 1 cm. The pause was followed by the active phase of the experiment when the barrage was removed and the pump was switch on. Water was supplied to the tray for a specified time. After that the pump was switch off, the barrage was re-installed, and the resulting capacity was filled with water. For the first few seconds of the active phase the particles that lost their bonds with the soil mass of sample were washed out from the surface of the sample. One can visually observe this process on the tray in the form of flowing mass of soil particles (Fig. 4), whereas in the traditional method of testing samples individual particles or groups of particles can be rarely observed. With the increase in the duration of pauses, the number of particles that lost their bonds increased slightly with deceleration (Fig. 5). This can be explained by two factors. The accumulation of particles deprived of bonds presses increasingly on the underlying soil lays, making the spread of the bond destruction process into the sample (substance) more difficult or even impossible. Another explanation may lie in the fact that the molecular movement of water between soil particles slows down as the front of seeping water lowers. This leads to reduction in the rate of breaking ties between particles.

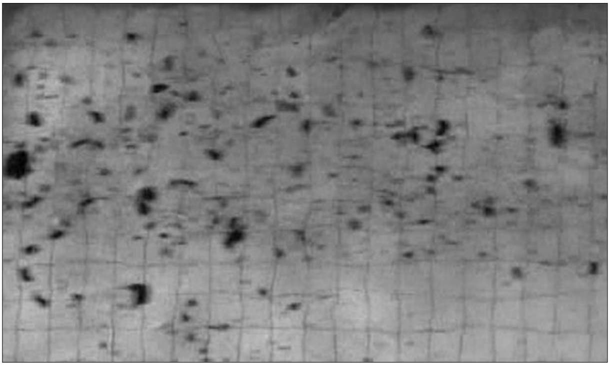

Fig. 4. View of the tray below the sample. Dark spots are disrupted soil particles and groups of particles by the flow.

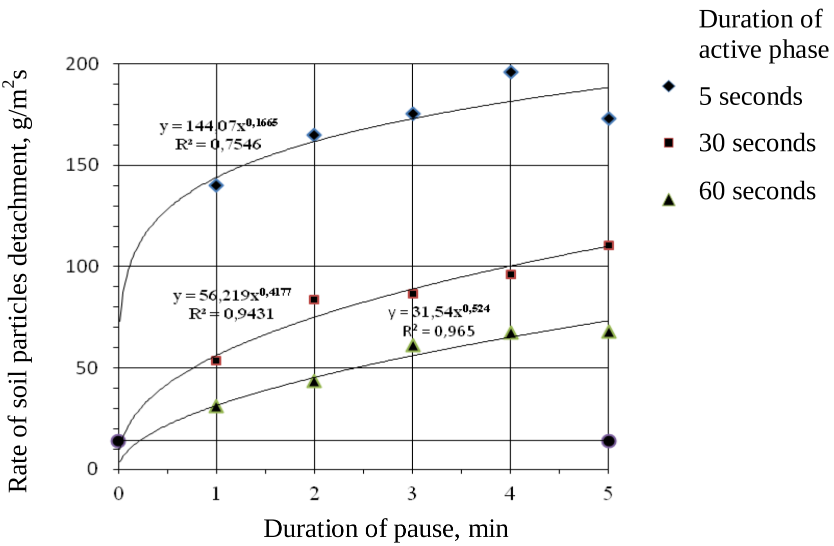

Fig. 5. Slowing the rate of erosion of the sample with increasing duration of the pause.

The maximum detachment rate of soil particles decreases with the increase in the duration of pauses, which reflects the slowdown in the destruction of the inter-aggregate bonds as active front penetrates deeper.

This character of soil particles detachment in our opinion can only be explained by the fact that the force of non-hydraulic genesis, namely the strength of intermolecular interaction, plays the leading role in breaking bonds between particles. Taking into account this circumstance, a sharp turning point on the graph of relationship between the intensity of flushing and the cubed speed (Fig. 2) can be explained at the following way. On the first steep section of the curve, the rate of destruction of bonds between particles occurring under the action of the dipole molecules of water is faster than the entraining by the water flow of soil particles freely lying on the sample surface. As the flow velocity increases, the intensity of the particles capture grows, along with accelerated exposure of soil sample layers – with still intact bonds between soil particles – to the action of water as a chemical substance. In other words accelerated detachment of free particles increases the rate of bond destruction even between consolidated particles. However when the ability of the flow to capture non-consolidated particles exceeds the rate of particles deconsolidation by water, the graph levels off sharply. With further increase of the water flow velocity, hydraulic forces start to take part in the destruction of bonds between soil particles in the surface soil layer, and probably the contribution of hydraulic forces would increase with the increase of the flow velocity. It is possible to prove and quantify this phenomenon only experimentally.

The abovementioned facts mean that hydrostatic pressure probably influences the rate of water-caused destruction of bonds between the particles. This can take place, assuming that the hydrostatic pressure does not extend deep into the soil sample. This hypothesis was confirmed experimentally in 4 experiments in the hydraulic tunnel, in which the hydrostatic pressure was maintained in one case, about 0, and the other about 1 atmosphere. In the second case, the rate of erosion of soil samples, and therefore, the rate of destruction of bonds between soil particles by water as a chemical substance was substantially lower than in the first one (at zero hydrostatic pressure).

Finally, we can assume that the bond between the soil particles is ensured not only by the van Der-Waals forces, but also, for example, by polymer compounds. To confirm this hypothesis, several samples were dried and then moistened to its original status and then tested on erosion. And this assumption was confirmed. After drying the samples almost did not erode. Since under natural conditions, the soil is still washed out it was hypothesized that the bonds between particles can break down also under the influence of cyclic wetting and drying, as well as other factors of weathering.

Thus, the results allowed us to identify the mechanism of destruction of the bonds between soil particles in the process of water erosion, which will serve as the basis for developing physically based erosion models.

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