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Hydrology

Modern Methods of Calculating the Prediction of Water Erosion

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ABSTRACT. The method of predicting erosion is further perfected. The coefficients entering the former equation are specified through the use of the so-called fatigue theory of erosion. *© 2007 Bull. Georg. Natl. Acad. Sci.*

Key words: *erosion, prediction, scour, fatigue.*

The damage done by erosion does not point to the need of stopping the agricultural development of soils, urbanization, etc., for that would mean simultaneous suspension of the development of human society in general. Hence, one should look for ways out of these critical situations, since the circumstances noted above are not inevitable and there certainly are ways of slowing the negative tendencies. Soil – the most valuable of all the treasures on earth – fully merits to be managed reasonably and thriftily, with a view of preserving ecological stability, on the basis of the latest achievements not only of the soil erosion science but of related branches as well [1-6].

The overwhelming majority of “troubles” observable at the development of impermissible accelerated erosion on slopes may be averted or substantially reduced through modern prediction – of course preferably quantitative. Such an approach allows cultivation of slopes prone to erosion without substantial losses of soil, with account of the real conditions of exploitation and rational selection of the most optimal ways of protecting soils from erosion.

As is known, any science goes through a number of stages, including that of perfecting the approaches it has at its disposal. The branch studying erosion should not be taken for an exception. Here, too, new concepts have to be introduced, allowing a deeper insight into the problem under study. The diversity and complexity of investigations carried out do not allow a comprehensive discussion of all aspects.

By the scale of spread and summary damage caused by soil erosion, erosional processes and their concomitants (mudflows, landslips, desertification) may be assigned with good reason to hazardous natural disasters. Erosion – acting as it does without much “noise” – is more insidious and no less harmful than other well-known negative processes. Therefore, interest in it does not diminish either on the side of states or researchers. It is worth noting that prior to the proclamation by the UN of a new global strategy of fight for the reduction of the consequences of natural disasters the science of soil erosion built its strategy on the early recognition of soil scour [3].

The tendency to closer quantitative mathematical description of individual processes of erosion led to the development of prediction problems in the non-classical statement at scientific centres of the former Soviet Union, if classical is reserved for the USLE method that was usefully applied in the US and other countries for over 50 years [1, 6].

Mankind has sought to work out fairly precise methods of predicting soil scour since the very first days of civilization. However, work on this has become more purposeful since the time of organization of the service of soil protection in the USA.

The methodology presented to the 3rd Hydrological Congress in 1957, devoted to analytical determination of non-scouring velocities for cohesive soils, is considered to have been the date of emergence of analytical methods of quantitative estimation of soil erosion [5]. The methodology just cited took fairly full account of the physico-mechanical properties of soils and the hydromechanical parameters of flow, in contrast to the hitherto existing method based on the qualitative assessment of only soil types. The prior importance of this approach lies not so much in its potentialities of quantitative determination of the non-scouring velocity for cohesive soils according to the actual physico-mechanical characteristics of resistance to scour and in initiating a number of studies but also – as pointed out by K.V. Grishanin [7] – "in reflecting the probabilistic character of the start of movement of soil particles". And this process, as Albert Einstein noted in a conversation with his son, "is too complex". [8].

Further, with the aid of one of the major indices of hydrology and mechanics of liquids (of the non-scouring velocity of a water flow), in the 1960s an equation of soil scour, based on the fatigue theory of separation of aggregates, was derived with the aid of the laws of mechanics [3]. Fatigue implies loosening of the links of aggregates with the soil mass under dynamic impact of the pulsating slope runoff.

The equation for predicting soil scour in the course of time *I* has the form:

$$q_{x_2T} = 11 \cdot 10^{-3} y\omega d \left[\frac{308(\sigma\, n_0)^{0.6} i^{0.7} m_1^{1.4} J^{0.6} x_2^{1.6}}{V_{\Delta\partial on}^2} + \right.$$

$$\left. + \frac{13 \cdot 10^{-6}\, V_{\Delta\partial on}^{3.32}}{(\sigma\, n_0) i^{1.16}\, m_1^{2.32} I} - x_2 \right] \frac{T}{x_2} \frac{Tona}{ga} \qquad (1)$$

where γ is the volume weight of soils under full water saturation, t/m^3;

d is the average size of aggregates (separating particles), reduced to the diameter of an equal-volume sphere. In the absence of data of special studies the size of an aggregate is taken to be d=3÷5 mm; on the average d=0.004 mm. According to the data of Moscow State University, for arable horizons of soils developed on moraine and loess-like loams for soils of plain areas of the European part of the former USSR the value of *d* does not exceed 1-2 mm, equaling 0.5 mm, on the average [5];

$V_{\Delta\mathrm{perm}}$ is the permissible near-bed non-scour (non-eroding) velocity of flow of the water stream;

ω is the mean frequency of pulsation velocity. It may be determined by the Strouhal number ω=0.73$V{\cdot}H$ (V is the mean velocity of slope runoff, H is the depth of runoff). In the absence of data of special studies the value of ω is assumed to equal 10 *l*/sec.

I is the average intensity of precipitation m/sec;

T is the duration of excessive rainfall or the time in the course of which the layer of precipitation exceeds that of infiltration;

σ is the coefficient of runoff;

n_0 is the coefficient of hydraulic resistance (Manning coefficient);

i is the average slope of surface, equal to the ratio of the difference of the levels of the contour interval of the slope according to A.N. Kostyakov [2,9], coefficient describing the roughness of the slope surface, the concentration of runoff;

Equation (1) – called 'hydromechanical' in the literature – at verification, shows a fairly satisfactory agreement with observation data. Notwithstanding its considerable age, the formula remains competitive to the present day. This property is due to its being simple to master and apply – its potentialities of constant perfection. However, further analysis points to the need of some specification. After all, it is sometimes useful to complicate the theory in order to reflect the real situation of the process more correctly and precisely than to use too idealized assumptions.

An analysis of experimental studies has shown that at the initial moment of impact of slope runoff on soil, when the actual velocities (hence the power action exerted by them) considerably exceed the non-scouring velocities for the given soil, the detachment of particles occurs over a relatively short time interval – over a small number of cycles of change of loads. At the end of deformation – at the point of stabilization – the number of load cycles needed for the detachment of particles approaches infinity. An analogous picture is evidenced at testing samples of clayey soils for 'fatigue' breaking strength. Experiments show that with an increase of dynamic load (and stress) the number of cycles necessary for the rupture of the sample decreases.

On the basis of [9], the curve of 'fatigue' strength may be approximatively expressed by the dependence:

$$N = N^* / (\sigma_H / \sigma_K - 1), \qquad (2)$$

where N is the number of stress cycles; σ_H and σ_K are the breaking stress respectively at the initial and final moments of load impact; N^* is the dimensionless coefficient depending on the characteristics of flow and properties of soils under erosion, $N^* = 1888000$, then.

$$N = 180000 / (\sigma_H / \sigma_K - 1). \qquad (3)$$

The term 'fatigue' is applicable in explaining the breakdown of links as a result of the action of cycle loads over a certain period of time. Dynamic loads on the bed are due to the near bottom velocities of water flow at the initial and final moments of deformation $V_{\Delta i}$ and $V_{\Delta f}$; the latter, at full stabilization, is equal to the permissible non-scouring near-bottom velocity $V_{\Delta b}$. In expressing the stress of aggregate detachment through these velocities, the dependence (2) assumes the form:

$$N = N^* / \left(V_{\Delta H}^2 / V_{\Delta b}^2 - 1 \right). \tag{4}$$

Hence it follows that when the flow down the slope is powerful, the detachment of aggregates occurs more intensively. With the reduction of runoff the erosional process occurs more intensively. With an increase of runoff the erosional process dies down. Thus, there is an analogy between the separation of a soil aggregate under the dynamic action of pulsating turbulent flow and the rupture of soil samples as a result of the impact of dynamic load. Hence the detachment of particles from a water-course bed bottom, formed of clayey soils, may be described by the equation (4).

When the average frequency of pulsation velocities ω is known, the time needed for the detachment of a particle may be determined.

$$\tau = N / \omega = N^* / \left[\omega \left(V_{\Delta H}^2 / V_{\Delta b}^2 - 1 \right) \right. . \tag{5}$$

Consequently, the number of particles detached from a section $\ell \times \ell$ over one second will total:

$$n_1 = 1 / (N / \omega), \tag{6}$$

where V is the mean velocity of flow, H is its depth.

It is important to note that the characteristics of the 'fatigue' breaking strength of soil subject to erosion, which is the basis for determining the number of detaching particles, cannot be obtained directly from other mechanical properties; it should be measured or determined indirectly.

It would probably be more correct if the numerator of the formula (3) were also a measurable value, e.g. one most fully characterizing erosion by erosion resistance, i.e., by permissible non-scouring flow velocities. These indices may be determined with fair precision, depending on the flow parameter and soil properties. In the dynamics of river-bed flow [3] fairly well-grounded expressions are available for calculating this widely applied parameter, and a standard has been developed.

The proposed improvement of the model enables to determine the type of the 'fatigue' curve. Incidentally, identification of 'fatigue', depending on the relation of the acting near-bottom velocities to permissible non-scouring near-bottom velocities without carrying out tests of 'fatigue' scour, is usually rather difficult and laborious [3].

The sought values are determined from the equation (5), solving it relatively to N^*:

$$N^* = \tau\omega \left(V_{\Delta x}^2 / V_{\Delta perm}^2 - 1 \right), \tag{7}$$

As shown by the results of forced (accelerated) tests of soil scour, the value of N^* often differed from the values calculated by the formula (5): N^*=188000. Such a value corresponds to soils characterized by permissible (non-scouring) velocities $\left(V_{perm}\text{=}0.12 \div 0.13 \text{m/c} \right)$; with an increase of permissible velocities this index grows.

The results of numerous experiments on accelerated testing of soil scour of varying composition, provenance and geographic location (hundreds of samples of soils of intact composition have been tested from the route of the main canal Siberia – Middle Asia) have enabled to find the function of $N^* = f\left(V_{\Delta gen} \right)$, where N^* has been calculated by the dependence (5), when the experimental values of $V_{\Delta perm}, V_{\Delta_x}$ are known.

Approximation of he curve allowed to obtain a formula for determining the coefficient of N^*, depending on the erosional resistance of soils expressed by the most important index, namely the permissible (non-scouring) velocity of flow, which reflects both the resistance of soils to erosion and the value of the non-silting velocity of flow:

$$N^* = 3 \cdot 10^6 \left(V_{\Delta per} - 0.5 V_{\Delta nonsilt} \right) \ell^{-\sqrt{V_{\Delta per}}}, \tag{8}$$

$$N^* = \frac{3 \cdot 10^6 \left(V_{\Delta gen} - 0.5 V_{\Delta nonsilt} \right) \ell^{-\sqrt{V_{\Delta gon}}}}{V_{\Delta_x}^2 / V_{\Delta perm}^2 - 1}. \tag{9}$$

It should be noted that the above analysis of the results of studies is not definitive, and may be made more precise in the course of emergence of more detailed data. As is known [3], the number of detached aggregates from a 1×1 plot per second totaled $n_1 = 1 / N / \omega$

Substituting the value of N from formula (8) in the expression n_1 we obtain:

$$n_1 = \omega \left(V_{\Delta_x}^2 / V_{\Delta perm}^2 - 1 \right) / 3 \cdot 10^6 \left(V_{\Delta perm} - 0.5 V_{\Delta nonsilt} \right) \ell^{-\sqrt{V_{\Delta perm}}}. \tag{10}$$

At the time of stabilization of scour the value of the acting near-bottom velocity approximates the permissible (non-scouring) near-bottom velocities. Practically, erosion ceases when the near-bottom velocity of surface runoff $V_{\Delta_x} \approx 1.15 V_{\Delta perm}$.

Substituting the value n_1 in (1) and taking into account the experimental data, as well as the fact that the number of aggregates of d size per unit of the width of the river-bed $m_2 = \alpha_2 / d$, an expression of silt at uniform movement of flow:

$$q = 4 \cdot 10^{-7} \gamma \omega d \left(V_{\Delta_x}^2 / V_{\Delta perm}^2 - 1 \right) /$$

$$3 \cdot 10^6 \left(V_{\Delta perm} - 0.5 V_{\Delta nonsilt} \right) \ell^{-\sqrt{V_{\Delta perm}}} . \qquad (11)$$

For the discharge of silt at a site at the distance Δ_x from the origin of the watershed, under the known averaged value of the near-bottom velocity at the interval Δ_x, the expression will assume the form:

$$q_{\Delta x} = 4 \cdot 10^{-7} \gamma \omega d \left(V_{\Delta_x}^2 / V_{\Delta perm}^2 - 1 \right) \Delta x /$$

$$\left(V_{\Delta perm} - 0.5 V_{\Delta nonsilt} \right) \ell^{-\sqrt{V_{\Delta perm}}} . \qquad (12)$$

As we are discussing the process of erosion, it is obvious that the value V_{Δ_x} will always be greater than the non-scouring velocity of flow for the given soil.

The total discharge of silt per unit of time from an area on a slope, whose length is x, while the width equals unity, may be determined by integrating the expression (11) between O and x.

The earlier dependence [3, 9] proves valid for the condition $V_{\Delta perm} = 0.12 - 0.13$ m/s:

$$q_{\Delta x} \approx 64 \cdot 10^{-7} \gamma \omega d \left(V_{\Delta_x}^2 / V_{\Delta perm}^2 - 1 \right).$$

In case it proves unfeasible to integrate the expression for V_{Δ_x}, the total discharge of silt is obtained by final summation or graphically.

The velocity of the movement of slope runoff, needed for solving the task set, may be determined by the formulae presented in [3], depending on the intensity of rainfall, absorption of water by the soil per unit of time, the distance from the watershed, slope gradient, the roughness factor according to Manning, the height of the roughness protuberances.

Active erosion will last until the saturation of the slope runoff reaches the limiting transporting capacity. If we designate the distance from the watershed to this point x_1, the length of the section of active erosion will total [3]:

$$l_{act} = x_2 - x_1 , \qquad (13)$$

while the length of the accumulation section at the slope length x:

$$l_{accum} = x - x_2 , \qquad (14)$$

Substituting the value $V_{\Delta_x} = V_{\Delta perm}$ in the equation (11), we shall obtain the length of the non-eroding section of the slope:

$$x_1 = V_{\Delta_{perm}}^{3.32} / 22.2^{3.32} m_1^{2.32} 1^{\cdot 1.16} n_0 (I - k) =$$
$$0.000034 V_{\Delta_{perm}}^{3.32} / m_1^{2.32} 1^{\cdot 1.16} n_0 (I - k), \qquad (15)$$

where the coefficient m_1 varies from 1 to 3; at transverse ploughing its value is less than at longitudinal ploughing.

If the coefficient of pressure loss is expressed through the height of roughness protuberances according to V.N. Goncharov $- n_0 = \Delta^{1/16} / 22.2$ [6], we shall obtain:

$$x_1 = 0.00075 V_{\Delta_{perm}}^{3.32} / m_1^{2.32} 1^{\cdot 1.16} \Delta^{0.17} (I - k) . \qquad (16)$$

Substituting the value V_{Δ_x} [3] in the equation (11) and bearing the foregoing in mind, as well as data of laboratory and experimental studies carried out in various soil and geologic, geographic and hydrological conditions, following integration, adding x_1 according to the dependence (16) and multiplying by the time T, we obtain the discharge of silt (t/m):

$$q_{x_2} = \frac{0.2 \gamma \omega d}{\left(V_{\Delta perm} - 0.5 V_{\Delta nonsilt} \right) \ell^{-\sqrt{V_{\Delta perm}}}} \times$$

$$\times \left[\frac{308 (I - k)^{0.6} t^{0.7} m_1^{1.4} n_\omega^{0.6} x_2^{1.6}}{V_{\Delta perm}^2} + \frac{0.000013 V_{\Delta perm}^{3.32}}{(I - k) t^{1.16} m_1^{2.32} n_0} x_2 \right] T \qquad (17)$$

and the value of the soil scour (t/ha)

$$q_{x_2 T} = \frac{2 \cdot 10^3 \gamma \omega d}{\left(V_{\Delta perm} - 0.5 V_{\Delta nonsilt} \right) \ell^{-\sqrt{V_{\Delta perm}}}} \times$$

$$\times \left[\frac{308 (\sigma n_0)^{0.6} t^{0.7} m_1^{1.4} I^{0.5} x_2^{1.6}}{V_{\Delta perm}^2} + \right. \qquad (18)$$

$$\left. + \frac{13 \cdot 10^{-6} V_{\Delta perm}^{3.32}}{(\sigma n_0) t^{1.16} m_1^{2.32}} - x_2 \right] \frac{T}{x_2} .$$

Notwithstanding the above-said, experience of solving analogous tasks suggests that complex models should be avoided, no matter how elegant they may be. Reasonably approximative solution of a problem should be considered acceptable. Such models merit preference, for they permit measurement of the parameters involved in the expressions. One should not be oblivious of the fact that it is not only the models that err but input data as well, which are very often very difficult to determine with prescribed precision. The precision of input data has a poor reputation in connection with their errors. Problems exist also in the methods of measurement and in the devices themselves. Therefore, one should not expect the models being created, no matter how perfect, to yield precise results. In this connection interest attaches to the statement made by the American Robert Aumann, winner of the Nobel Prize, to the effect that “Scientific theories may be judged by how well they allow to organize our observations”. Of course, one should reject outright the temptation to solve a task purely empirically, because of the well-known shortcomings. Hence, the proposed specifications ought to be used only for highly responsible items.

Under the present status of the study of the erosional process, it seems to be more important to concentrate the basic thrust of investigations on the solution of tasks that allow to take timely adequate measures in order that calmly proceeding erosional processes do not develop into landslides, mudflows or – at long-term neglect – into desertification.

ჰიდროლოგია

წყლისმიერი ეროზიის პროგნოზირების თანამედროვე მეთოდები

ც. მირცხულავა

აკადემიის წევრი, წყალთა მეურნეობის ინსტიტუტი, თბილისი

მოცემულია ნიადაგის წყლისმიერი ეროზიის პროგნოზირების ადრე შემოთავაზებული (1970 წ.), ე.წ. ჰიდრომექანიკური მეთოდის შემდგომი სრულყოფა.

გაუმჯობესებისას საპროგნოზო დამოკიდებულებაში ეროზიის დაღლილობის თეორიის გამოყენებით დაზუსტებულია განტოლებაში შემავალი კოეფიციენტები. დაკვირვებების მონაცემების შედარება თეორიულ გათვლებთან დამაკმაყოფილებელია.

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