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Land erosion, research equipment, forecasting methods and prospects for their improvement

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ABSTRACT The present work describes the erosion process by means of a simplified mathematical model reflecting recent advances in the relevant sciences. Methods of field investigation involving the use of mobile sprinklers and a gauge for measuring cohesive forces characterizing resistance to scour are described. A systems approach to erosion studies is advocated.

Erosion du sol, équipement de recherche, méthodes de prévision et perspective pour leur amélioration
RESUME On décrit le processus d'érosion à l'aide d'un modèle mathématique élaboré a partir des derniers progrés dans ce domaine. On expose également la méthodologie de recherches sur le terrain à l'aide de simulateurs de pluie mobiles. On décrit un appareil de mesure des forces de cohérence caractérisant la résistance à l'érosion. On démontre les avantages de cette approche des processus d'érosion.

AN EROSION MODEL

Soil surface erosion caused by flowing water has influenced human activity, and man has felt its unfavourable effects since the very beginnings of his existence. Man has also tried to control erosion processes with both positive and negative outcomes. Erosion following reduction of infiltration, for example, has reduced not only the soil resources of a country, but also its water resources. Erosion is often the source of pollution of streams and drainage basins. Rational planning of reliable measures to combat erosion, reduction of soil losses to permissible limits and optimal use of agriculture first require accurate forecasts of soil erosion rates based on the basic causative factors (Mirtskhoulava, 1967, 1970).

Although any model is a simplified representation of reality, a mathematical model for a quantitative estimation of separate erosion processes should describe these processes quantitatively and qualitatively with sufficient accuracy. In the early 1960's the author developed a modelling approach to describe the erosion process by means of a simplified mathematical model, which incorporated recent advances in relevant sciences including hydrology, hydraulics, pedology and soil mechanics. In addition to traditional indices, the model of slope erosion takes into account, amongst other variables, the noneroding velocity of sheet flow, hydraulic resistance, the effect of initial moisture, and man's economic activities. Inclusion of these factors in the model enables prediction of the sediment discharge generated by rainstorms, and facilitates proper planning of vegetation cover for slopes (Mirtskhoulava, 1970, 1974, 1976, 1978). The present approach allows a more rigorous and exact description of erosion processes. However, it should be admitted that the model of the erosion process is only a simplified analogue of reality, and erosion predictions, therefore, have to be verified with data from further field studies. Such investigations are being undertaken at our Institute (Dokhnadze, 1980).

An erosion plot, measuring 2 x 10 m and 2 x 8 m, was constructed for this purpose. It was oriented with its long axis in the downslope direction. The plot was defined on three sides by metal sheeting inserted to a depth of 10 cm. Runoff was measured by a weir in the flume at the outlet of the plot, and measures were taken to prevent leakage across the plot boundaries. Simulated rainstorms were created by use of a street washing truck with a capacity of 6000 litres. It was equipped with a sprinkler device which produced a relatively uniform rainfall intensity over the experimental plot. Pumping equipment was employed to vary the waterhead and a pressure from 1×10^5 to 8×10^5 Pa could be generated. The sprinkler was set up on the upslope side of the experimental plot at a height sufficient to create the necessary rainfall intensity. Ten totalizer gauges, with an intake area of 200 cm^2, were spaced evenly over the experimental plot and were used to determine the value of rainfall intensity. The rainfall intensity (I) was defined according to the average value of the water volume collected in the gauges. Rainfall intensity and duration and total area of the plot were used to calculate input of rainfall per minute and total receipt during the whole experiment. The runoff from the experimental plot was observed and the commencement and the cessation of runoff were noted. The amount of plot runoff and discharge hydrographs were determined from changes of water stage at the weir and a runoff coefficient σ was also computed.

Runoff from the plot was sampled for suspended sediment and the quantity of soil which settled in the flume was measured at the end of the experiment. In addition, soil samples were taken for laboratory analysis to determine the initial moisture and physicomechanical characteristics of the ground surface. The soil state, vegetation cover, beginning of erosion, and number of rills formed were also recorded.

Slope wash values obtained in field investigations were compared with model predictions (Mirtskhoulava, 1970, 1976, 1978) obtained according to the equation:

$$q_{x_2 T} = 11.10^{-4} g\rho\omega d \left[\frac{308(\sigma n_0)^{0.6} i^{0.7} m_1^{1.4} I^{0.6} x_2^{1.6}}{V_{\Delta per}^2} + \frac{13.10^{-6} V_{\Delta per}^{3.32}}{(\sigma n_0) i^{1.16} m_1^{2.32}} - x_2 \right] T \qquad (1)$$

where:
q_{x_2T} is the slope wash (t ha^{-1});
ρ is the soil density (kg m^{-3});
g is the acceleration of gravity (m s^{-2});
ω is the average frequency of pulsating velocities; it can be established according to the Strouhal number $\omega = 0.73\ V/H$; where V is the mean velocity of the sheet flow and H is the sheet flow depth; when data are lacking to compute ω, it was assumed to equal 10 s^{-1};
d is the mean diameter of entrained aggregates, assumed equal to 0.004 m (Mirtskhoulava, 1967);
σ is the runoff coefficient;
m_1 is a coefficient accounting for the deviation of the sheet flow motion from the accepted smooth water level motion;
I is the average intensity of precipitation (m s^{-1});
n_0 is the roughness coefficient (Manning's coefficient);
$V_{\Delta per}$ is the permissible noneroding velocity of the bed (m s^{-1});
i is the average surface slope;
x_2 is the length of the plot (m);
T is the duration of excessive precipitation(s).

The relatively high intensities of artificial rainfall minimized the importance of the second term in equation (1), which can be effectively ignored in predictions. Some of the data obtained from our experiments are presented in Table 1. The roughness coefficient (Dokhnadze, 1980) used in erosion predictions was established by the modified method of Goncharov (1962). Predicted and experimental data exhibit a good correspondence and suggest the model is successful in approximating the erosion process. However, it was also established that the prediction equation was less successful when the effects of vegetation cover and agricultural practices are simulated. Some results using an improved model have been presented by Dokhnadze (1980).

MEASUREMENTS OF SOIL COHESION

Investigation of numerous soils of different origin and geographic location have been carried out (Mirtskhoulava, 1967), and have shown quite a strong correlation between scouring velocities and cohesion, the latter reflecting the whole complex of physico-mechanical and chemical features which produce resistance to scour. Resistance to scour increases with the growth of cohesive forces between aggregates and individual particles. Thus cohesion of soils is considered to be not only an index of soil strength, but also a physical feature of great interest in estimation of resistance to erosion. The significance of cohesion in soil resistance makes the accurate determination of cohesion an important consideration. A number of methods have been applied to the measurement of cohesive forces, but these methods inadequately define the strength of cohesion between aggregates and individual particles and, in turn, the resistance offered by the soil to the scour process.

In consequence, a new method has been developed over the last

Table 1 Results of experiment carried out on slopes planted with agricultural crops

Plot characteristics	Plot gradient	Plot length (m)	Initial moisture (%)	Rainstorm intensity ($m\ s^{-1}$)	Duration of precipitation excess (s)	Runoff coefficient σ	Design value of roughness coefficient	Permissible (nonscouring) bed velocity ($m\ s^{-1}$)	Wash erosion ($t\ ha^{-1}$)	
									According to equation (1)	From experimental results
1. Beetroot, closely planted; experiment carried out before weeding	0.26	10	9.4	0.000 019	2880	0.06	0.031	0.12	3.34	2.95
2. Beetroot, closely planted; experiment carried out before weeding	0.26	10	31.2	0.000 026	1170	0.13	0.031	0.12	3.12	4.19
3. Beetroot, closely planted; experiment carried out before weeding	0.26	10	30.2	0.000 027	330	0.14	0.031	0.12	0.95	1.60
4. Beetroot; experiment carried out after weeding; grass cut during weeding is removed from the plot	0.26	10	11.4	0.000 047	1140	0.05	0.025	0.10	3.21	11.96
5. Beetroot; experiment carried out after weeding; grass cut during weeding is removed from the plot	0.26	10	32.1	0.000 028	510	0.11	0.025	0.10	1.71	3.46
6. Beetroot; experiment carried out after weeding; grass cut during weeding is removed from the plot	0.26	10	16.6	0.000 020	1140	0.14	0.025	0.10	3.53	4.73
7. Potatoes; before weeding	0.16	7	23.8	0.000 011	3120	0.04	0.046	0.14	0.20	0.25
8. Potatoes; before weeding	0.16	7	19.0	0.000 015	4500	0.04	0.046	0.14	0.59	0.65
9. Potatoes; after weeding, grass cut during weeding is removed from the plot	0.16	7	7.8	0.000 012	3300	0.02	0.025	0.11	0.08	0.05
10. Potatoes; after weeding weeding; grass cut during weeding is removed from the plot	0.16	7	12.2	0.000 012	2700	0.03	0.025	0.11	0.18	0.16

decade at our laboratory to establish the cohesive forces of soils in a totally saturated condition. The technique is based on a strong correlation between cohesion and the depth of local scour caused by the application of a jet of water to a saturated soil (Mirtskhoulava, 1980). It has been established experimentally under controlled conditions that the cohesive force of a soil is inversely related to depth of local scour generated by a water jet. These experimental findings are in agreement with the theory of scour processes. Given the experimental conditions and knowing the head and discharge of water, the cohesion force may be calculated according to the following equation:

$$C = 16(ud^*/(H+20d^*))^2 \tag{2}$$

where C is cohesion (10^4 Pa); H is depth of local scour, caused by the falling jet (m); u is velocity of outflow from the nozzle ($m\ s^{-1}$); and d* is diameter of nozzle hole (m). This equation has been obtained from theoretical analysis of extensive data which have been derived from experimental investigation of clay soils of various consistencies and origins, and in disturbed and undisturbed states.

The experimental results from the hydrojet method are sufficiently reliable to indicate that the technique can accurately estimate cohesion of soils in the state of total water saturation and hence their stability under erosion. It should be noted that estimates of the erosional stability of soils based on the water jet principle have had a long history. However, to the author's knowledge, the equation presented here is the first relationship which allows quantitative prediction of cohesion from measurements made in a simple experiment. The numerical coefficients in equation (2) may be altered in the light of further investigations, but their present values are considered to predict cohesion with an acceptable accuracy.

The present technique may be used in conjunction with an ordinary water supply which has a permanent head, or with any source, providing a pump is available to create a water jet. The influence of initial moisture conditions on the experimental result is eliminated by wetting the test soil through capillary action until it is totally saturated with water. The technique described in the present paper differs from existing methods in its simplicity, quickness and accuracy. The method is considered to produce very reliable values of soil cohesion because resistance to the processes of scour and erosion is measured directly.

A SYSTEMS APPROACH TO EROSION STUDIES

The paper is concluded by stressing the advantages of a systems approach to studies of soil stability and erosion. Soil, as the most valuable part of the biosphere, cannot be considered separately from the multitude of environmental factors which influence pedogenesis, including the many and varied measures of conservation taken to protect the soil system. The enhancement of soil stability and protection from erosion is dependent on a large number of interconnected factors, which have to be considered as part of the whole soil system. When the soil resources of the biosphere are utilized by man, each method of soil improvement, such as irrigation, drainage and use of fertilisers, will exert both direct and less easily detectable indirect influences on other soil processes.

Intensification of agricultural production and the various processes this entails have given rise to new interdependent phenomena. Over the last few decades not only the slope of land under agriculture, but also the machinery and methods of soil cultivation, harvesting and sowing have been radically changed. Cultivated soils may be subject to feedback mechanisms which produce stabilization through slope levelling and smoothing, or protection by paving of the erodible surface.

The soil system has to be controlled in order to attain a given level of stability, and a variety of scientific and engineering approaches are currently available to achieve this end. The best method of protecting a soil against erosion is to encourage a well developed vegetation cover in optimal positions on a slope according to the methods presented by Mirtskhoulava (1970, 1974). Arguments in favour of a systems approach to the solution of soil erosion problems are numerous, although the advantages of the approach are evident from the selected examples presented in this paper. Systems analysis must be the basis of soil management if one of the most important natural resources is to be exploited successfully.

Application of a systems approach to soil management is beyond the competence of a specialist in a single discipline such as pedology or hydraulic engineering and requires the cooperation of workers in many other fields including hydrology, climatology, mechanical engineering, mathematics, physics, chemistry, statistics, cybernetics, biology, agronomy and economics. Reliable solutions or even promising progress in the problem of soil management can only be expected on the basis of a systems approach and from the joint efforts of specialists working in different countries under various geographical, geological, climatic and economical conditions.

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