Laboratory Experiment and Theoretical Analysis of Dynamic Parameters for Water Erosion Prediction Model

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Abstract: Water erosion is a complicated physical process. The prediction model is a powerful tool to research the mechanism of water erosion and more and more attention has been paid to the physical- process-based soil erosion prediction model. The parameters used in the erosion prediction model should have a specific physical meaning and could be expressed by a mechanical function or measured by experiment, which is the key points for the sound application of soil erosion prediction model. A series of integrated experiments were designed to obtain the parameters used in the water erosion prediction model under the different hydraulic conditions (different slopes and in-flow rates). Considering the fact that, under steady flow, sediment concentration increases with slope length and will finally approach that corresponding to the sediment transport capacity, a laboratory flume experimental method with variable slope length is advanced for transport capacity determination. And a mathematical expression is suggested to estimate the transport capacity with thus obtained experimental data. A series of 405 flume experiments were conducted with sand-clay (loess) soil. Transport capacity is related to slope gradient and inflow rate. Based on the experiments thus made, a method was advanced to compute the detachment rate of sediment loading water flow, under the assumption that the flow and soil are behaving the same way along rills. Then detachment rates were presented as functions of sediment concentration and rill length.
Keywords: water erosion prediction model, detachment rate, sediment transport capacity, analytical method

1 Introduction

Soil water erosion, as a complicated physical process with the transfer of energy and materials, is the major erosion phenomenon worldwide. Soil erosion is the external agent to cause the transfer of soil materials. Water erosion process includes the soil detachment, sediment transport and on-site and off-site sediment deposition. With the help of soil erosion model, the prediction of soil erosion has been studied. Study of soil erosion mechanism helps to develop a reasonably sound soil erosion prediction model while soil model made in certain time presents the research level of that time. Soil erosion model, based on the understanding of soil erosion mechanism and processes, is a group of mathematical functions, expressing various processes. Soil erosion prediction model provides a tool to estimate soil erosion intensity and could be a base for land use planning, soil erosion prevention engineering project.

Research of soil erosion on uplands used to start from observation and quantitative description of erosion related parameters to gain experiences, to form theories and to develop models. Soil erosion researches are dated back to the end of 18^{th} century and the beginning of 19^{th} century. From 1877 to 1895, Wollny, a Germany scientist, constructed the first experimental plot of soil and water conservation research to observe effects of vegetation and surface coverage on soil erosion prevention and soil sealing, and effects of slope gradients on surface flow and soil erosion. Afterwards, such plot experimental methods has been being widely used in United States of America and Russian, as well as many other countries. And also the method had been further improved. Nearly all of these are researches of application and based on the experiences. Research of soil erosion mechanic started from 40s of 20^{th} century. Zingg presented a prediction model of sheet erosion and rill erosion. From the middle of 50s, a series of wider, more dedicated and systemic projects were conducted, which opened a new phase of soil erosion research. It is especially worthwhile mentioning that based on the multi-regression experiments, Wischmeier and his colleagues presented USLE, which is a factorial expression. With the help of statistics, they found a correlated relationship between the soil loss values obtained from plots across USA and the multiplication of rainfall, slope length, slope gradient, vegetation coverage, management practice, and soil conservation measures. Until the end of 60s, Meyer and Wischmeier developed a process-based technology on the base of soil erosion knowledge. However, the technology was not used due to self-contained data and limited computer capability.

At present the best yet empirical soil erosion model is RUSLE, with advantages such as its simple form and relatively ease estimation of model parameters, and disadvantages as its incapability of predicting dynamically spatial and temporal soil erosion distribution. RUSLE, capable for land use evaluation and planning, is limited in selecting soil conservation measures. Therefore, more attention has been paid to the study of soil erosion processes so as to overcome the problems of empirical models.

The physical process-based model emerged in 60s of 20^{th} century. From the physical conception of sedimentation, runoff and sediment transport, mathematics, meteorology, hydrology, hydraulics, soil science and sediment mechanics, were used by the researchers to relate erosion processes with various influencing factors to simulate special and temporal soil erosion.

In 1969, Meyer and Wischmeier presented a process-based soil erosion and sediment transportation model, which divided the water erosion process on upland into 4 sub-processes, and established a quantitative relationship among the 4 sub-processes. However, all components in model are merely determined theoretically. Till 70s, the process-based model presented by Foster and Meyer was applied widely. The model used mass transfer continuity function to describe sediment movement along slope while sediment detachment in rill and interrill were still expressed by USLE.

After 1980s research on soil erosion process enjoyed a rapid progress as the result of combination of demand and possibility. People gained more knowledge of soil erosion, and started to believe that soil erosion could be predicted. On the other hand, with the development of modern science and technology, improvement of instruments, high capability of computers, satellite and electronic technology, researchers could get more accurate data and great power of computation. With the help of numerical simulation, researcher could get the spatial and temporal features of soil erosion. As what Hempel said: scientific research in each fields cannot merely try to record the certain appearance in the world, but also to get a law among changing things in order to establish a general law to predict and explain the happening events. Therefore, based on the research of the soil erosion mechanics, phenomena of soil erosion processes were recorded and analyzed, and sedimentation relationship with the impacting factors were further analyzed to develop water erosion prediction models.

Since 1980s, research on soil erosion and sedimentation has been conducted in China. The Chinese Academician Huang B.W made a comprehensive study, which showed that water erosion on upland could be divided into two steps: soil particle detachment and sediment transport. He also pointed out that rill erosion play far more important role than raindrop splash and sheet erosion does. Tang L.Q set up a qualitative soil erosion model of watershed by analyzing the mechanism of soil detachment, transport and deposition. Cai Q.G divided watershed unit into finer sub-areas. Considering the complicated topography on Loess Gully regions and the sedimentation distribution, he modeled the soil erosion of the region in 3 sub-areas: top of the plateau, hill slope and gully. Shao X.J presented a one-dimensional kinetical wave model of rill and centered-flow on upland and gave the analytic method of model. Bao W.M presented a conceptual model for hill slope and gully sedimentation. Li Q.H analyzed the sediment model of upland from different perspectives. Up to now, China just started study of physical process based soil water erosion

The process-based model has a strong foundation of physics and is transferable to different conditions to simulate the spatial and temporal changes of soil erosion. The existing problem with physic process based model is that many model parameters are still empirical and difficult to be measured directly from designated experiments. Water Erosion Prediction Project (WEEP) is one of the most complicated computer models or simulation program to describe soil erosion processes till now. It could be used to simulate spatial and temporal processes of soil erosion. The problem is that some parameters, such as sediment detachment and transport capacity, can only be empirically determined.

To make soil erosion model based on process, parameters in the model should have physical meaning and can be expressed by mechanic functions or can be directly measured by experiments.

The study, conducted in Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, was to develop a method and an experimental procedure to determine various model parameters. It is known that rill erosion is the major factor affecting water erosion on upland. Therefore, this study focused on rill erosion. A series of experiments was conducted to address rill erosion dynamic process and the effects of in-flow rate and slope gradient was considered as influencing factors.

2 Material and methods

The experiments used three treatments: slope grade, slope length and flow rate. Five slopes (5º, 10º, 15º, 20º, 25º), 8 to 9 slope lengths (0.5 m, 1.0 m, 2.0 m, 3.0 m, 4.0 m, 5.0 m, 6.0 m, (7.0 m), 8.0 m), and 3 flow rates (2 L/min, 4 L/min, 8 L/min (i.e. 0.12 m^3/h, 0.24 m^3/h, 0.48 m^3/h)) were used. Three replicates were made for a total of 405 experiments.

The flume was put on a platform, which was adjustable to desired slopes. The flume was about 8 meters long and 1 meter wide that is divided into sections of 8 by 0.1 m. Flume walls were specially treated to reduce their influence on water flow and erosion processes by adhering soil to the flume walls to give them a roughness similar to that of the soil used in the experiments.

We used a silty-clay (loess) soil, typical of the Loess Plateau. The soil was air-dried and passed through a 10 mm sieve prior to measuring its density. A clay soil (particle size smaller than 0.01 mm constituting 56% by weight) was packed into the flume bottom at a depth of 30 cm, and was compacted to act as a non-erodible layer. The experimental soil was then packed loosely and evenly in the flume at a uniform depth of about 20 cm. The soil near the flume walls was slight higher than the middle surface in order to avoid the walls' influence on the erosion processes. The soil was then saturated and allowed to equilibrate for a day (24 hours) before each run in order to provide even initial water content and to eliminate any effects of uneven packing.

Tap water was supplied through a tank and pump, and the flow rate was adjusted and calibrated with a valve. Three hoses were used to supply water at the same rate to three adjacent flume divisions, representing 3 replicates. Small holes were evenly drilled in the outlet pipe of 9 cm wide, which was covered with gauze so as to assure an even distribution of water across the rill, and to eliminate a much as possible any disturbance of the soil surface.

When water flowing in the rill became steady, flow velocities were recorded along the rill with dye-tracing technique (Lei *et al*., 1998). Two to three sediment samples were taken from each outlet of the rills for sediment concentration.

3 Results and discussions

3.1 Sediment concentration and slope length

Sediment in water is subjected to several forces, including gravity, buoyancy, and turbulence. Sediment moves towards the rill bed due to gravitational forces, while buoyancy and turbulent forces tend to support and suspend sediment particles. As an example, the relationships between sediment load and rill length at a slope of 20° was shown in Fig. 1. It can be clearly seen that sediment concentration increases with rill length under the same discharge for each of 3 flow rates, but that the increase rate (the slope of the curve) diminished gradually. As expected, the sediment load approached a limiting value, which can be thought of as the value corresponding to the sediment transport capacity.

This is also true for the results of the other treatments.

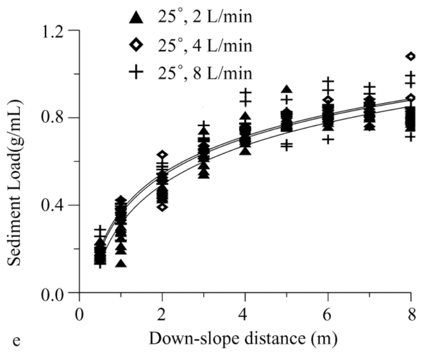

Fig. 1 Relationship between sediment load and rill lengths

3.2 Method to estimate transport capacity

To estimate transport capacity from the experimental data obtained, a mathematical model is advanced, which represents the rill erosion processes as discussed above and fits with the measured data. The relationship between sediment load and rill length for the given slope and inflow rate was regressed with the following model:

$$c = A(1 - e^{-\beta x})^{B} \quad (1)$$

where c is sediment load (g/ml, 10^3 kg/m^3), β is a reduction coefficient (also a regression coefficient), x is slope length (m), A and B are regression coefficients. Regressed coefficients of determination are between 0.8—0.96, which shows that the regression function has a high prediction precision.

The physical meanings of coefficients in the function are as follows: β and B are decay coefficients of sediment concentration with of increase of down slope distance; A is the maximum value of sediment concentration, that is, it represents the sediment load corresponding to transport capacity. When flow is saturated with sediment, the sediment concentration of the flow is given as $c = A$, and the net detachment rate D_r is zero. Therefore, from Eq. (1), the transport capacity is given as:

$$T_c = Aq \quad (2)$$

where, q = unit width flow rate of given flow (m^2/s).

Eq. (2) implies that transport capacity is directly proportional to A, the maximum sediment concentration. And the results showed that slope and in-flow rate have great effects on sediment capacity.

3.2.3 Computational method for estimating detachment rate with experimental data

Basic assumption for the estimation of detachment rate was: soil detachment behavior is the same along the rill under steady stream, i.e., for a given erosion driving force in any segment of equal rill length produces the same amount of sediment regardless of its location. Under this assumption, if sediment produced from a rill of x m is C and that from a rill of $x+\Delta x$ is $C + \Delta C$, then the increment in sediment yield ΔC can be reasonably thought as sediment detached from this rill segment increase Δx.

Then sediment detachment can be estimated with an equation equivalent to Eq. (3) as:

$$D_r = \frac{\Delta c\, q}{\Delta x} \quad (3)$$

where x (m) is rill length.

Detachment rates in the following sections were computed with the above-mentioned equation from the measured sediment yields related to different rill lengths. Fig. 2 showed the relationship between soil between soil detachment rate and sediment load while figure showed the relationship detachment rate and down-slope distance.

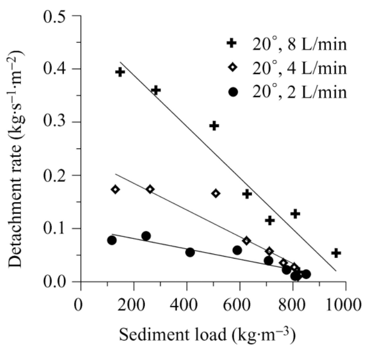

Fig. 2 Relationship between soil detachment rate and sediment load

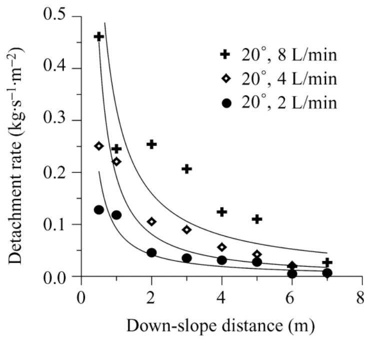

Fig. 3 Relationship between soil detachment rate and down-slope distance

4 Conclusions

A series of experiments were designed and conducted in aims of determining parameters of soil erosion models. Rills of variable lengths on different slope were subjected to concentrated water flow of different flow rates. Sediment concentration yielded was related to rill length. A method for determining sediment transport capacity was derived, based on the functional relation of sediment concentration and rill length. A method is outlined, to use the experimental data to compute soil detachment by water. Examples of soil detachment rate as function of sediment load and rill length were given. The procedure reported in this paper will be useful in determining parameters for soil erosion models.

Acknowledgment

This paper is based on the work supported by the Ministry of Education of China under Project No. ZD-0110 and by the Ministry of Finance of China under Project No. 982602.

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