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Erosion and sediment delivery in rills on steep loess slope*

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Abstract Sediment delivery in rills on the loess slope was studied by inflow experiments. Relationships between sediment delivery rate in rills and flow shear stress, discharge and slope gradient, maximum sediment and unit runoff power, and discharge and slope gradient were analyzed. A relationship is presented for calculating the erosion rate in rills.

Keywords: **rill erosion, critical shear stress, unit stream power, sediment rate.**

Rills are distributed widely and densely on slopeland and therefore rill erosion is a main sediment resource on hillslopes. Much improvement has been made on prediction of soil loss from rills on gentle slope; however, few studies are conducted on steep slope such as that in the Loess Plateau of China. In order to study rill erosion process and its mechanism, inflow experiments were conducted on the loess slope. The erosion and sediment delivery in rills were studied in this paper on the basis of the measurements and calculation of flow hydraulics in rill erosion.

1 Relationship between detachment capacity and flow shear stress

Flow detachment capacity refers to the capacity of flow to detach, suspend and deliver soil particles on slopeland, of which detachment and suspension are dominating process. In the 1940's, Shields deduced an equation for relating detachment of soil particle to shear stress in the study of sediment movement in rivers, and indicated that it is the flow shear stress that results in the departure of soil particle from soil surface. In the 1960's, Meyer calculated the flow detachment rate on slopeland using a simplified equation:

$$D_r = K_r(\tau - \tau_c)^a, \tag{1}$$

where K_r is the rill soil erodibility parameter, τ the flow shear stress acting on unit area of soil surface, τ_c the critical shear stress for the soil to be detached and a is a constant.

Afterward, many experiments were conducted to study the parameters in this equation under various soil conditions. Results show that the relationship between flow shear stress and detachment

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capacity satisties eq.(1) basically. On the other hand, the new study indicates that in rills detachment capacity of flow linearly depend on flow shear stress. Thus, in the USDA-water erosion prediction model, the constant a is set being unity to calculate the detachment capacity of flow.

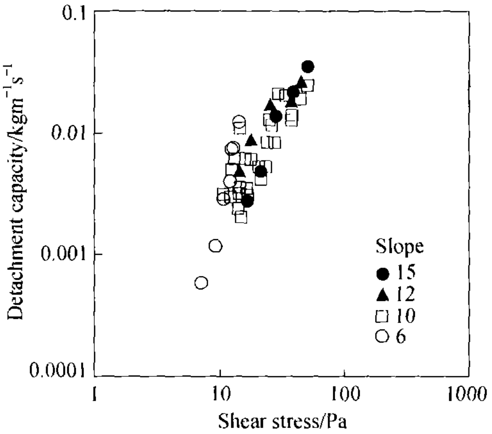

Fig. 1. Detachment capacity of flow in rills vs. shear stress.

For the studies of rill erosion on steep loess slope, the first thing is to testify the relationship between flow shear stress and detachment capacity, then to determine the loess erodibility parameter K_r, and critical shear stress for rill detachment τ_c. We plot the data from our experiments under different slope gradients and flow discharges in fig. 1. The data also indicate a good linear relationship between flow shear stress and detachment capacity. By regression analysis with 46 samples, eq.(1) is derived as

$$D_r = 8.18 \times 10^{-4}(\tau - 6.78), \qquad (2)$$

$$R = 0.8899,$$

where the rill soil erodibility parameter $k_r = 8.18 \times 10^{-4}$ s/m and the critical shear stress $\tau_c = 6.78$ Pa for rills on the loess slope.

2 Relationship of the maximum sediment load in rills with the discharge and slope gradient

Concentrated water flows down mostly in the state of turbulent flow on the steep slope sensitive to rill erosion. Consequently, the process of rill erosion behaves evidently as bursting events. The local shear stresses can be much greater than the average flow shear stresses. Corresponding to this behaviour of turbulent flow, sediment loads in rill erosion changes notably with the duration of runoff. In order to understand the mechanism of sediment loads of flow in rills precisely, it is necessary to study the change of maximum sediment loads along with the flow erosion capacity. Maximum sediment load in rills of different lengths is an important parameter describing the transport capacity of flow in rills.

Maximum sediment load depends on both flow detachment capacity and sediment supply. Flow detachment capacity is always great when discharge exceeds the threshold value, so the maximum sediment loads rely on the sediment supply to great extent on steep loess slope. In the experiments, the maximum sediment loads mainly appear soon after the occurrence of flow with the tendency that the more the discharge, the sooner the maximum sediment loads appear. For a certain kind of soil, the maximum sediment loads depend on flow discharge and slope gradient, their relationship in our experiments is shown in fig. 2. It shows that the maximum sediment loads of flow in rills are different on different slopes, but there is a tendency that the steeper the slope gradient, the higher the sediment loads. When the slope gradient is kept constant, the sediment loads increase with the increase of flow discharge as a whole. But there is a different tendency as the slope gradient changes from gentle to steep. The maximum sediment loads increase rapidly with the increase of flow discharge on gentle slope (6° in our experiment); while they change very little with the increase of flow discharge on 10°—12° slope. However, the maximum sediment loads increase rapidly again on 15° slope. Another

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important finding is that there is a limit for the maximum sediment loads on every experimental slope.

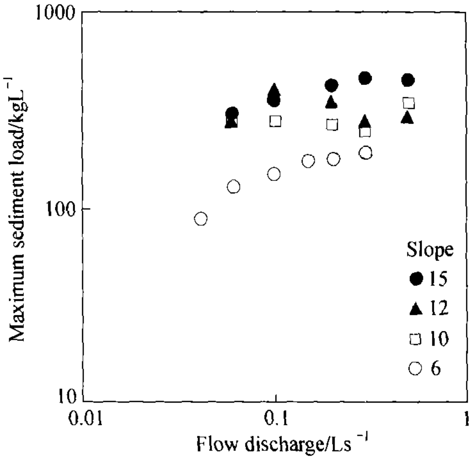

Fig. 2. Maximum sediment loads vs. flow discharge and slope gradient.

The above-mentioned phenomenon may be explained by the fact that on gentle slope, erosivity of unit flow is so limited that sediment loads depend mostly on flow discharge. However, on steep slope, erosivity of unit flow becomes greater, even a small flow discharge can erode and transport all soil particles supplied, so the maximum sediment changes very little with the change of flow discharge. However, when the slope gradient becomes more steeper, the maximum sediment increases again with the increase of flow discharge, owing to the more rapid increase of flow erosivity and the further deepening and widening of rills. The relationship between flow discharge, slope gradient and maximum sediment is derived by multiple regression analysis as follows:

$$S_{\max} = 11.89 Q^{0.1029} J^{1.137}, \tag{3}$$

where $S_{\max}$ is the maximum sediment in rill flow (kg/m^3), Q the flow discharge in rills (mL/s), and J the slope gradient. The coefficients in eq.(3) indicate also that the sediment loads depend on slope gradient more heavily than on flow discharges.

3 Relationship between maximum sediment loads and unit stream power

Although eq.(3) can be used to estimate the maximum sediment of flow in rills, it cannot reflect the detailed dependence of maximum sediment on flow discharges with different slopes. In order to further understand the intrinsic mechanism of sediment loads in rills, we must find another parameter to simulate the process of sediment yielding in rills. In the 1980's, Yang pointed out that a good relationship exists between unit stream power and sediment based on large amount of data from river sediment investigations. According to the definition by Yang, unit stream power is the potential energy dissipated in the process of water movement during unit time, which can be expressed as

$$P = \frac{\mathrm{d}y}{\mathrm{d}t}, \tag{4}$$

where $\mathrm{d}y$ is the increase of elevation of flow in the period of $\mathrm{d}t$. The equation can be transformed into

$$P = \frac{\mathrm{d}x}{\mathrm{d}t} \cdot \frac{\mathrm{d}y}{\mathrm{d}x} = VJ. \tag{5}$$

Eq.(5) indicates that unit stream power can be expressed in terms of the product of flow velocity and riverbed gradient or slope gradient. The variables in (5) have definite meanings and are easy to measure or calculate. According to the definition of unit stream power and data from our experiments, the

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relationship between unit steam power and maximum sediment in rills is plotted in fig. 3. The regression function is presented as

$$S_{\max} = 450 - 2.85(100P - 13)^2, \qquad (6)$$

$$R = 0.8553.$$

Eq. (6) suggests that there is a critical unit stream power P_c for the occurrence of rill erosion and a limit of maximum sediment load S_*. Under our experimental conditions, the critical unit stream power $P_c = 0.00434$ m/s, for the occurrence of rill erosion on loess slope, and the maximum sediment reaches its limit, $S_* = 450$ kg/m^2 when P is 0.13 m/s.

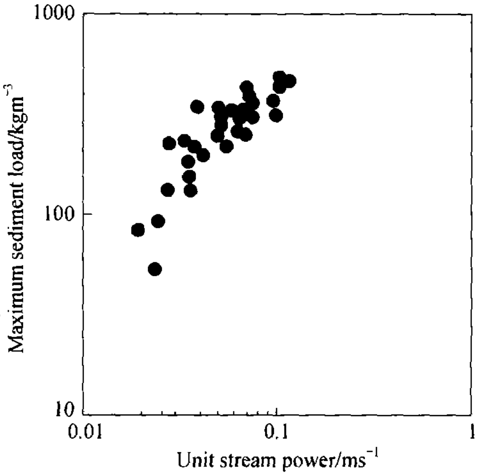

Fig. 3. Maximum sediment loads vs. unit stream power.

4 Conclusions

The results of experiments show that rill soil erodibility parameter, k_r, is 8.18×10^{-4} (s·m^{-1}) and the critical shear stress, τ_c, is 6.78 Pa on the tested loess slope. Sediment load varies greatly in the duration of runoff. Maximum sediment load changes with different trends as slope gradient changes from gentle to steep. In general, the steeper the slope gradient, the higher the sediment. When slope is kept constant, sediment load increases with discharge in general. A quadratic equation is derived to relate the maximum sediment to unit stream power in rills. The equation reveals not only the quantitative relation of sediment load to unit stream power, but also its clear physical meaning.

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