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A rational method for estimating erodibility and critical shear stress of an eroding rill

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Abstract

Soil erodibility and critical shear stress are two of the most important parameters for physically-based soil erosion modeling. To aid in future soil erosion modeling, a rational method for determining the soil erodibility and critical shear stress of rill erosion under concentrated flow is advanced in this paper. The method suggests that a well-defined rill be used for shear stress estimation while infinite short rill lengths be used for determination of detachment capacity. The derivative of the functional relationship between sediment yield and rill length at the inlet of rill flow, as opposed to average detachment rate of a long rill, was used for the determination of detachment capacity. Soil erodibility and critical shear stress were then regressively estimated with detachment capacity data under different flow regimes. Laboratory data of rill erosion under well defined rill channels from a loess soil was used to estimate the soil erodibility and critical shear stress. The results showed that no significant change in soil erodibility (K_r) was observed for different slope gradients ranging from 5 to 25 while critical shear stress increased slightly with the slope gradient. Soil erodibility of the loess soil was 0.3211 ± 0.001 s m^{-1}. The soil erodibility and critical shear stress calculations were then compared with data from other resources to verify the feasibility of the method. Data comparison showed that the method advanced is a physically logical and feasible method to calculate the soil erodibility and critical shear stress for physically-based soil erosion models.

Keywords: Soil erodibility; Critical shear stress; Soil erosion prediction model; Rational method; Loess soil

1. Introduction

Soil erosion is a serious environmental problem threatening the future development of agriculture and society. It is not only a major factor responsible for the long-term degradation of land quality, but also a major source of non-point water pollution. Increased attention to these concerns has led to improved measures for erosion control and a superior comprehension in soil erosion mechanics and soil loss prediction.

A process-based model for soil erosion prediction is a group of mathematical functions based on soil erosion processes. Scientists have developed and worked with these process-based erosion models, such as the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995), since the 1980′s. Soil erodibility (K_r) and critical shear stress (τ_c) are two important indices of soil properties and are used as essential parameters in WEPP (Nearing et al., 1989a) and are described in the following relationship:

$$D_r = K_r(\tau - \tau_c)\left(1 - \frac{qc}{T_c}\right) \quad (1)$$

where D_r is rill detachment rate, kg m^{-2} s^{-1}; τ is the shear stress of flowing water, N m^{-2}; τ_c is the critical shear stress of soil, N m^{-2}; q is unit flow rate, m^3 s^{-1} m^{-1}; and c is sediment

Abbreviations: D_r, rill detachment rate; D_{rmax}, potential detachment rate; T_c, transport capacity of the flowing water; WEPP, Water Erosion Prediction Project.

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concentration, kg m^{-3}; T_c is transport capacity of the flowing water, kg s^{-1} m^{-1}; and K_r is the erodibility of soil, s m^{-1}.

Gilley et al. (1993) suggested a method to estimate the soil erodibility and critical shear stress and is as follows. Field experiments of rain simulation with runoff plots of 0.46 by 9 m were run. Detachment rates under different flow rates were computed with collected runoff samples, and the shear stresses of the water flow were determined by the flow rates and slope gradients. These detachment rates and shear stresses were used to estimate the erodibility and critical shear stress as parameters in the following regression model:

$$D_{\mathrm{rmax}} = K_r(\tau - \tau_c) \tag{2}$$

where D_{rmax} is potential detachment rate. This method has been used to estimate soil erodibility and critical shear stress throughout the US (Elliot et al., 1989). Importantly, Eq. (2), as compared with Eq. (1), indicates that the potential detachment rate can only be estimated with clean water, in which $c=0$.

Under steady concentrated flow into a well defined (uniform slope with no variation in width) rill channel, the relationship between sediment concentration distribution in flow water and rill length was conceptually, numerically, and experimentally illustrated by Huang et al. (1996), Lei et al. (1998) and Lei et al. (2001), respectively as:

$$c = A\left(1 - e^{-\beta x}\right) \tag{3}$$

where, A and β are regression coefficients, varying with soil and hydraulic conditions; x is downslope rill distance, m.

This functional relationship indicates that sediment concentration increases with rill length and approaches a maximum value of A, the sediment concentration at transport capacity. The increase in sediment concentration, however, decreases exponentially with rill length. This incremental reduction in the rate of increase in sediment concentration is due to a decrease in soil detachment rate. This phenomenon of detachment rate reduction of sediment loaded flow has been experimentally demonstrated by Lei et al. (2002) and indicates that long rills give a very poor estimation of potential detachment rates. Based on this recognition, Huang et al. (1996) mentioned that in a rill detachment/transport model, a short channel is needed for the (potential) detachment rate. As a result, experiments on their small soil samples (12.7 cm in diameter) (Nearing et al., 1991; Nearing and Parker, 1994) gave much higher detachment rates than did the rill erosion experiments conducted by Laflen et al. (1991) and Nearing et al. (1999) because of the influences of sediment presence in the flowing water, as discussed by Cochrane and Flanagan (1997) and Merten et al. (2001).

The objectives of this study then were to: 1) develop a method to estimate detachment capacity of steady rill flow, based on the sedimentation process of rill erosion and the rational estimation method of detachment rate as a function of rill length; 2) outline a rational method for the determination of soil erodibility and critical shear stress; and 3) estimate the soil erodibility and critical shear stress of a loess soil, with the newly suggested method.

2. Methodology

When the sediment concentration in rill channel flow is zero, the detachment rate approaches its maximum value, or reaches its potential detachment rate or detachment capacity. Under this condition, Eq. (1) is reduced to Eq. (2), which is also equivalent to:

$$D_{\mathrm{rmax}} = K_r\tau - K_r\tau_c \tag{4}$$

Sediment content in the rill flow comes from soil detachment in the rill bed by flowing water. The detachment rate is defined as the amount (kg) of soil detached from a unit area (m^2) in a unit time (s). Based on the mass balance, Rose et al. (1983) proposed the sediment continuity equation. When the rill length approaches zero at the upend where clear water is introduced into the rill, we assume that the sediment concentration in clear water of rill channel flow is zero, thus the sediment continuity equation based on mass balance is derived as,

$$\frac{\partial(cq)}{\partial x} + \frac{\partial(ch)}{\partial t} = 0 \tag{5}$$

where, c is sediment concentration, kg m^{-3}; q is flow rate per unit rill width, m^2 s^{-1}; x is down slope distance, m; h is flow depth, m; and t is time, s.

For the unit area, $\frac{\partial(ch)}{\partial t}$ is taken as the detachment rate (D_r). An analytic method for determining detachment rate of concentrated steady flow in eroding rills was advanced by Lei et al. (2002) under a given initial and boundary condition:

$$D_r = \lim \frac{\Delta c}{\Delta x} \cdot \frac{Q}{w} = \frac{d(qc)}{dx} \tag{6}$$

where, Q is inflow rate, m^3 s^{-1}; and w is rill width, m.

This equation means that the rill detachment rate under steady flow is the change rate of the sediment concentration in the flowing water, with respect to rill length, times the flow rate of unit rill width. Or equivalently, the soil detachment rate is the change in sediment yield with respect to rill length. Eq. (6) requires that the unit flow rate be uniform along the rill. The sedimentation processes, as related to rill length, or the relationship between sediment concentration and rill length is given in Eq. (3). Once the sedimentation process and the relationship between sediment concentration and the rill length are determined, the detachment rate can be easily obtained. It is done by substituting Eq. (3) into Eq. (6), yielding:

$$D_r = q\beta A e^{-\beta x} = T_c \beta e^{-\beta x} \tag{7}$$

where, T_c is transport capacity of flowing water, kg m^{-1} s^{-1}.

The detachment rate as expressed in Eq. (7) decreases exponentially with rill length. Depending on the actual value of β, the reduction in detachment rate at a given rill length varies. At a rill length of $x=3/\beta$, the detachment rate is reduced to 5% (exp $(-3)=0.05$) of the potential. Therefore, the average detachment of a long rill as a potential detachment rate vastly underestimates the detachment capacity. This explains why the small soil samples (12.7 cm in diameter) (Nearing et al., 1991;