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Modeling soil detachment capacity by rill flow using hydraulic parameters

Dongdong Wang [a], Zhanli Wang [a,b,*], Nan Shen [a], Hao Chen [a]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China

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SUMMARY

The relationship between soil detachment capacity (Dc) by rill flow and hydraulic parameters (e.g., flow velocity, shear stress, unit stream power, stream power, and unit energy) at low flow rates is investigated to establish an accurate experimental model. Experiments are conducted using a 4 × 0.1 m rill hydraulic flume with a constant artificial roughness on the flume bed. The flow rates range from 0.22×10^{-3} m^2 s^{-1} to 0.67×10^{-3} m^2 s^{-1}, and the slope gradients vary from 15.8% to 38.4%. Regression analysis indicates that the Dc by rill flow can be predicted using the linear equations of flow velocity, stream power, unit stream power, and unit energy. Dc by rill flow that is fitted to shear stress can be predicted with a power function equation. Predictions based on flow velocity, unit energy, and stream power are powerful, but those based on shear stress, especially on unit stream power, are relatively poor. The prediction based on flow velocity provides the best estimates of Dc by rill flow because of the simplicity and availability of its measurements. Owing to error in measuring flow velocity at low flow rates, the predictive abilities of Dc by rill flow using all hydraulic parameters are relatively lower in this study compared with the results of previous research. The measuring accuracy of experiments for flow velocity should be improved in future research.

1. Introduction

The Loess Plateau in China is one of the most severely eroded regions in the world (Chen and Luk, 1989; Fu and Gulinck, 1994; Jiang, 1997; Shi and Shao, 2000; Tang, 2004; Wu and Yang, 1998; Zhang and Liu, 2005). Rills are distributed widely and densely on slopes, and therefore rill erosion is the main sediment sources on hillslopes (Zhang and Zhang, 2000). Soil erosion occurs by overland flow following the detachment and displacement of soil particles (Govers, 1990). The detachment of soil particles by rill flow is crucial to sediment generation on hillslopes in the Loess Plateau.

Soil detachment is the separation of soil particles from the soil matrix at a particular location at the soil surface by erosive agents (Ellison, 1947; Wang et al., 2014; Zhang et al., 2003). Different relationships for soil detachment by rill flow are used in soil erosion models to estimate erosion rates by scouring in rills (Govers et al., 2007; Laflen et al., 1991). Understanding the basic mechanisms of soil detachment is essential in order to develop physically based erosion equations for use in developing soil erosion control measures (Laflen et al., 1991; Lal, 1994).

Erosion models are effective tools for predicting soil erosion and making decisions concerning soil erosion control, such as the Water Erosion Prediction Project (WEPP) (Nearing et al., 1989), the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965), the European Soil Erosion Model (EUROSEM) (Morgan et al., 1998), the Griffith University Erosion System Template (GUEST) (Misra and Rose, 1996), and the Limburg Soil Erosion Model (LISEM) (De Roo et al., 1996). Soil detachment capacity (Dc) is a key parameter in WEPP and other process-based erosion models. Given the widespread use of detachment prediction methods, their rigor is critical to the development of process-based erosion models.

In the past decades, numerous investigations were conducted to study the mechanisms of soil detachment by rill flow. The results indicate that soil detachment is strongly influenced, and in some cases controlled, by hydraulic parameters, such as flow regime, discharge, slope gradient, flow depth, velocity, friction, and sediment concentration (Cochrane and Flanagan, 1997; Govers et al., 1990; Govers, 1992; Nearing et al., 1991, 1999; Zhang et al., 2002, 2003, 2008, 2009). Dc increases with flow discharge and slope gradient, but it is more sensitive to flow discharge (Nearing et al.,

* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China. Tel./fax: +86 29 87010778.
E-mail address: zwang@nwsuaf.edu.cn (Z. Wang).

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1991). It increases as a power function of either flow discharge or slope gradient, both of which have been shown to be useful predictors of Dc (Nearing et al., 1999; Zhang et al., 2002, 2003). The results of these studies indicate that a logarithmic relationship exists between the detachment rate and the parameters of flow depth, slope, and mean weight diameter (Nearing et al., 1991). The detachment rate by rill flow is also known to decrease as sediment loads increase, because the energy expended to transport sediments is increased, thus reducing the energy available to detach new soil particles (Moore and Burch, 1986; Nearing et al., 1991). As sediment concentrations in the flow increase, the detachment rate in rills declines because of the feedback relationship between sediment load and detachment rate (Govers et al., 2007; Knapen et al., 2007; Merten et al., 2001). Therefore, the maximum soil detachment rate, which occurs when the sediment concentration in the flow is zero, is termed Dc.

The hydraulic parameters commonly used in simulating detachment rates are shear stress (Nearing et al., 1991), stream power (Hairsine and Rose, 1992a,b), and unit stream power (Morgan et al., 1998; Yang, 1972). Rill detachment rates are also better correlated with the power functions of shear stress and stream power (Nearing et al., 1999). Soil detachment by shallow flows is more closely correlated with flow energy than with shear stress (Zhang et al., 2002). Some studies indicate that stream power is better than shear stress for Dc prediction (Cao et al., 2009; Knapen et al., 2009; Zhang et al., 2003).

The hydraulic characteristics of flow and the properties of soil detachment at low flow rates, which are also important for soil detachment models, differ from those at high flow rates. However, little or no data exist regarding soil detachment processes at low flow rates (<0.00067 $m^2 s^{-1}$ used in this study).

Overall, despite the various studies, the hydraulic parameter best suited to describing soil detachment during erosion remains unclear. The problem is complicated by the difficulties in separating detachment and transport processes, and the interaction of the two processes in many rill experiments. This debate indicates that the fundamental mechanisms of detachment in rills are not fully understood. Therefore, more controlled laboratory research is required to better understand the relationship between soil detachment rate and hydraulic variables (Zhang et al., 2002).

The objective of this study is to investigate the relationship between the Dc by rill flow and hydrodynamic parameters, as well as establish a new and more accurate experimental model of Dc by rill flow at low flow rates.

2. Materials and methods

2.1. Test locations and soil

Experiments were conducted at the Simulated Rainfall Hall of the Institute of Soil and Water Conservation, Chinese Academy of Sciences. Test soil was loessial soil sourced from Ansai, Shaanxi Province, and soil mechanical composition was showed in Table 1, contents of soil organic matter is 0.3–0.6%. To remove stones, grass, and other debris from the soil, the air-dried sample was sieved through a 2 mm mesh, wetted by light spraying to achieve a soil water content of 14%, and equilibrated for 48 h in a plastic bucket. The soil sample box was packed to a bulk density of 1.2 g cm^{-3}. Immediately prior to the start of the experiment, the soil sample box was installed into the sample hole in the flume bed, with the elevation of the sample top kept even with the flume bed (Zhang et al., 2002).

2.2. Experimental design

To render rill erosion, detachment capacity was measured in a 4×0.1 m hydraulically adjustable flume. The slope of the flume bed could be adjusted between 8.8% and 46.6% to within 0.05% of a desired slope. Test sediment was evenly and smoothly glued to the surface of the flume bed to ensure that grain roughness remained constant for all the experiments (Zhang et al., 2008). Five flow rates (0.22, 0.33, 0.44, 0.56, and 0.67×10^{-3} $m^2 s^{-1}$) and five slope gradients (15.8%, 21.3%, 26.8%, 32.5%, and 38.4%) were tested, with each combination of flow rate and slope gradient tested twice, resulting in a total of 84 experiments.

For each experiment, the loess sample was packed into the soil box (10.5 cm in length, 9.9 cm in width, and 5 cm in depth) and placed in the flume, with the soil surface flushed with the flume bed surface. A cover panel was used to prevent soil samples from scouring before the sample surface was adjusted to be even with the flume bottom. Flow rate, which was controlled by a series of valves, was determined by collecting water flowing to a graduated container within a given time frame. The flow discharge was applied to the flume from the upper edge. Once setup was complete and the flow stabilized, the panel was removed and the detachment experiment was initiated. Experiments were timed as soon as they began, and ended when the depth of the eroded soil in the soil sample box reached 1.5 cm. The wet soil was oven-dried at 105 °C for 24 h and then weighed.

2.3. Determination of hydraulic parameters and detachment capacity

2.3.1. Flow rate and water depth

Flow rate was measured directly using a calibrated flow meter. When the flow stabilized, flow depth was measured by a level probe (±0.01 mm) at points 0.02, 0.62, and 1.22 m above the lower end of the flume. At each distance, depths were measured twice, at points 1.0 cm from each side and at the center of the flume, resulting in a total of 9 positions and 18 measurements for each experiment. The mean flow depth for each combination of flow rate and slope gradient was defined as the average of the 18 measurements.

2.3.2. Velocity

Velocity of the flow surface was determined using $KMnO_4$ as a tracer. Velocity measurements were replicated nine times. The water temperature was monitored. Reynolds number (Re) was calculated, and mean flow velocity was obtained by multiplying the surface velocity by 0.6 where the flow was laminar, by 0.70 where the flow was transitional, and by 0.80 where the flow was turbulent (Abrahams et al., 1985).

2.3.3. Hydraulic parameters

Shear stress (τ, measured in Pa; Nearing et al., 1991), stream power (ω, measured in W m^{-2}; Bagnold, 1966; Prosser and

Table 1
Soil composition.

Granulometric class	Clay	Silt	Very fine sand	Fine sand	Coarse sand
Particle size (mm)	<0.002	0.002–0.05	0.05–0.1	0.1–0.25	>0.25
Percentage (%)	5.95	61.17	27.67	5.22	0