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Detachment of road surface soil by flowing water

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ABSTRACT

An agricultural watershed generally consists of two land use categories, farmland and the unpaved road or path networks with different traffic frequency and size. Road surfaces are quite different from farmland soil in physical properties, resulting in it's distinguish production transportation process. Hydraulic flume experiments were conducted with the flow discharges ranging from 1 to 5 L s^{-1} and the slope gradients ranging from 8.8% to 46.6% to simulate the soil detachment process on a road surface and to develop tools in order to calculate detachment rates occurring on that road surfaces. The results illustrate that road surfaces behave characteristically in the runoff detachment and sediment delivery process due to the difference in the bulk density and functions of agricultural soils. The soil detachment rate is closely related to flow depth, slope gradient and other hydraulic parameters such as shear stress, stream power and unit stream power. Multiple non-linear regression analyses indicate that detachment rates for all roads can be accurately predicted by power functions of flow depth and slope gradient. According to the experimental results, stream power was suggested as an indicator to estimate soil detachment rate instead of shear stress in soil erosion models. However, considering the simplicity and availability, power function of flow depth and slope gradient is also recommended to predict detachment rate on the road surfaces.

1. Introduction

Erosion models are effective tools to predict soil loss. Since 1965, models such as 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), of which USLE has been widely used, have been developed to predict soil loss. The USLE provides an estimation of the long-term average annual soil loss from segments of arable land under various cropping conditions; however, sometimes in conservation planning and assessments the soil loss from a single storm is more distinguished than the average annual soil loss. In order to predict soil loss more precisely, process-based models such as the Water Erosion Prediction Project (WEPP, Nearing, et al., 1989) have been developed. Process-based models can predict where and when erosion is occurring by representing the essential mechanisms controlling erosion as detachment, transport, and deposition of soil particles (Foster, 1982). Mathematically describing these mechanisms is the essential process of erosion modeling (Lal, 1994). Among these processes, the detachment of sediment from the soil surface is very important to soil erosion. Hence, the optimization of detachment prediction methods is critical to the development of process-based models.

Soil detachment is defined as the dislodging of soil particles from the soil mass by raindrops and overland flow (Owoputi and Stolte, 1995), of which, overland flow scouring is the dominant process to detach and transport soil particles. In the past 30 years, several experiments have been conducted to investigate characteristics of soil detachment by open channel flow. Lyle and Smerdon (1965) reported a unique relationship between soil erosion and flow shear stress for a given soil type by using flumes of constant slope. Experiments using hydraulic flumes with varying bed slopes were conducted by Nearing et al. (1991) to evaluate the relationship between soil detachment rate and parameters such as shear stress and stream power. The results indicated that the logarithm relationship exists between detachment rate and parameters of flow depth, slope and mean weight diameter. The detachment rate for a given soil material is not a unique function of either shear stress or stream power. In their field experiments on rill detachment, stream power was found to be a good predictor for unit sediment load (Nearing et al., 1997). Later experiments showed that rill detachment rates were better correlated to a power function of either shear stress or stream power (Nearing et al., 1999). Zhang et al. (2002, 2003) conducted experiments in flumes on steep slopes ranging up to 46.6% with compassed and undisturbed soil samples respectively. They reported that the detachment rate could be well predicted by a power function of discharge and slope gradient. Stream

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power was better correlated to detachment rate than other hydraulic parameters. Hydraulic parameters normally used by researchers to simulate detachment rates are shear stress (Nearing et al., 1991), stream power (Hairsine and Rose, 1992a,b) and unit stream power (Yang, 1972; Morgan et al., 1998).

These researches have made a substantial contribution to the understanding and evaluation of soil detachment occurring on farmland soils. However, land use and human practices in rural watersheds typically consist of farmlands and unpaved road and path networks. Especially in the loess plateau of China, unpaved roads are a significant land use type in rural watersheds. Compared with farmlands, road surfaces may limit infiltration and increase the rate of sediment production in watersheds (e.g. Dunne, 1979; Reid and Dunne, 1984; Fahey and Coker, 1989; Ziegler and Giambelluca 1997). Also, road networks can influence and change hydrologic and geomorphic processes greatly in watersheds (Wemple et al., 2001). The road in effect can extend the reach of stream channel network by creating obstacle free pathways for sediment to move. Another distinguished difference between road networks and farmed surface is that the surface material is disturbed frequently by traffic activities and loosen materials are prepared in arid and semi-arid areas. Therefore, at the basin scale, road networks may affect runoff products and soil loss greatly owing to the inherent differences in soil properties and the channeling of water. In order to evaluate the effect of road network on soil loss in watersheds, the efforts are needed to understand the process of sediment and runoff generated on road surface itself, and to quantify the impacts of road network on the channeling of water and sediment delivery efficiency in a watershed. Although some studies have been conducted on road surface sediment generation, unfortunately, until now, relatively few attempts have been made to understand the detachment occurring on road surfaces. The objectives of this study are to: (1) examine the relationship between soil detachment rate on road surfaces and flow shear stress, stream power, and unit stream power, (2) develop equations that can be help to select parameters predicting soil detachment rates on different road surfaces.

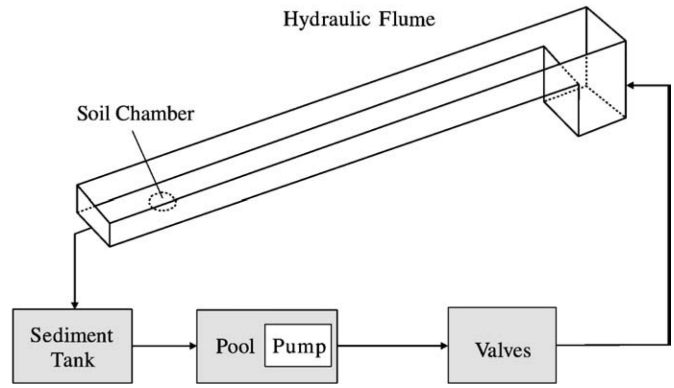

Fig. 2. The structure of the experimental devices (software used: CorelDraw).

2. Materials and methods

2.1. Sampling area and road categories

Experiments were conducted at Ansai Research Station of Soil and Water Conservation, Chinese Academy of Sciences, located in the centre of the loess plateau of China (Longitude 109° 19′23″ E, Latitude 36° 51′30″ N). The annual precipitation is about 549 mm, the mean temperature is 8.8 °C, and the elevation ranges from 1068 to 1309 m. The study area is a typical agricultural region where unpaved roads, constructed for farming, harvesting, and other objectives, are distributed widely throughout the watershed. During a rainstorm, runoff and sediment are commonly re-routed and enhanced by road networks. Indeed, unpaved roads function as channels to transport water and sediment, and even initiate gully erosion in some cases.

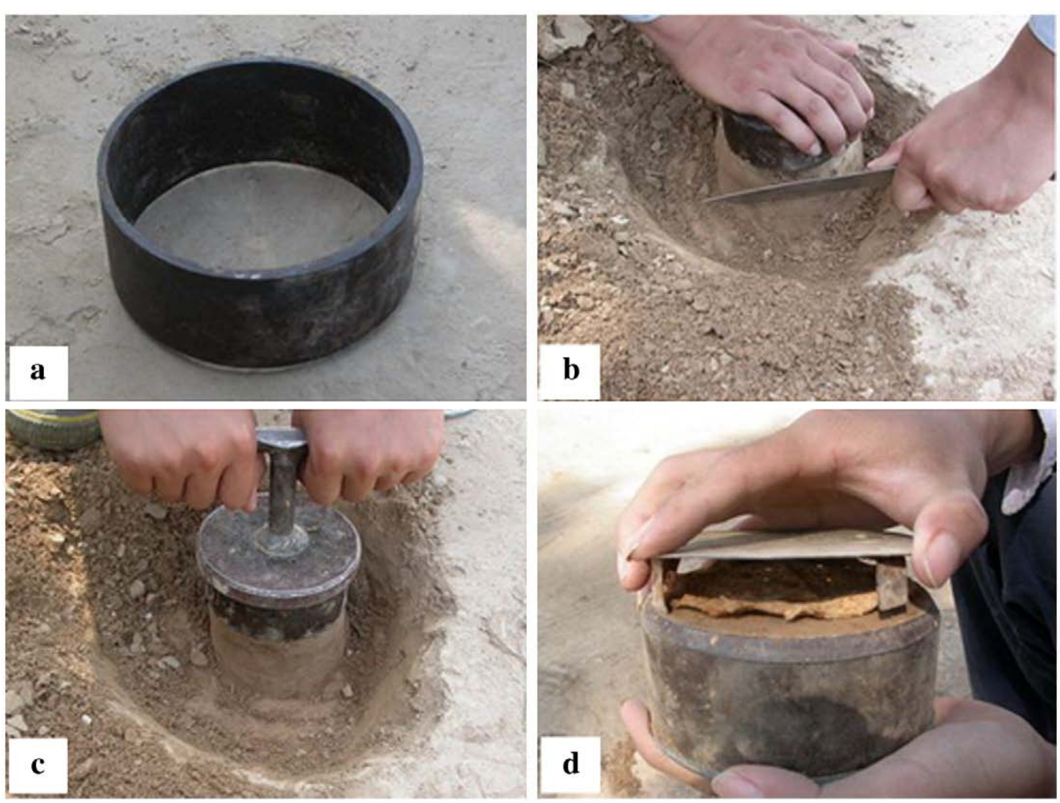

Fig. 1. The process of taking samples from road surface with an iron ring (software used: ACDSee and Microsoft Paint).