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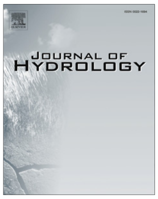

Effect of stone content on water flow velocity over Loess slope: non-frozen soil

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ABSTRACT

Stony soils are commonly found worldwide and are considerably studied for their hydrological characteristics and effect on soil erosion. Water flow velocity is an important parameter in understanding the effect of stone content on hydrodynamics and soil erosion. In this study, laboratory experiments were used to measure rill flow velocity by using electrolyte tracer method under different hydraulic conditions: flow rates of 1, 2, 4, and 8 L/min, slope gradients of 5°, 10°, 15°, and 20°, and stone mass contents amounting to 0%, 10%, 20% and 50%. Nine sensors, which were 1 m apart along the 8 m long rill, were used to measure flow velocity by tracing solute transport. Measured flow velocity increased with slope gradient and flow rate. The highest increase in flow velocity was measured from 15° to 20° which were also affected by flow rate. Effects of discharge rate on flow velocity presented the largest difference when flow rate increased from 2 L/min to 8 L/min at slope gradients higher than 5°. The effects of different factors were quantified by a regression model with high accuracy of 0.99. Maximum flow velocity of water was predicted at 15.23% of stone content. Flow velocity increased with 0–15.23% of stone content but decreased at higher values. This study aims at further understanding the hydrodynamics of soil erosion and sediment transport behaviors in hillslopes with different stone contents to obtain information for quantifying soil erosion on stony slopes.

1. Introduction

At the surface or within soil matrix, geographical phenomena involving stones are commonly observed in many regions of the world, such as Europe (Martínez-Zavala and Jordán, 2008), Australia (Sheridan et al., 2007), America (Lewis et al., 2006), Asia (Gale et al., 1993) and Antarctic Peninsulas (Golledge, 2014). Soils with high stone or rock fragment contents develop from both natural processes and anthropogenic factors, including tillage, grazing, and exploitation (Guo et al., 2010).

At low degree of development, the parent soil materials on steep hillslopes contain significantly high contents of stone or rock fragments (Urbanek and Shakesby, 2009). Removal of soil materials by erosion leave out stones contained in the surface soil layer. As soils are more easily scoured and transported than the stones, soil particles are eroded, whereas stones remain, causing direct contact of water flow with stones or rock fragments and subsequently affecting flow velocity. Then, ploughing or cultivation of arable land results in mixing of stone or rock fragments with the topsoil. Stone or rock fragment cover is also a well-known method for preserving soil moisture and protecting cultivated land from rill and interrill erosions (Romkens, 1985). This farming technique uses stone or rock fragments as mulch to improve crop productivity and is practiced by farmers for thousands of years in many semiarid regions of the world (Li et al., 2007). This protective effect results from the following: stone or rock fragment cover reduces soil erodibility by protecting soil surface against raindrop impact and flow detachment; soil surface mulching by stones enables water flow to carry less sediments; sediment detachment and transport capacity are significantly reduced as consequences of the effects of stone or rock fragments on flow velocity (Poesen et al., 1994; Abrahams et al., 2001).

Hydrological effects of stone or rock fragments on topsoil layers received considerable attention in recent decades. Soil stone or rock fragment content significantly influences soil infiltration, rill generation, soil erosion process, flow velocities and sediment transportation capacity (Leighton-Boyce et al., 2003; Van Wesemael et al., 2006; Martínez-Zavala and Jordán, 2008; Urbanek and Shakesby,

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2009). Commonly, scientists believe that increase in stone or rock fragment content decreases velocity of water flow (Agassi and Levy, 1991; Poesen, 1992; Poesen et al., 1994; Nyssen et al., 2001; Guo et al., 2010; Majed et al., 2011). Bunte and Poesen (1993) measured erosion rate and average flow velocity with laboratory experiments at 0.014 slope gradient and discharge rates of 84 cm^3/s to 91 cm^3/s. Results indicated that average flow velocity decreased exponentially when rock coverage increased from 0% to 25%. Velocity value of 25% rock coverage reached one third of bare soil and remained unchanged at higher values of rock coverage. Poesen et al. (1999) measured flow velocity by using dye tracing technique over rock-fragment-covered soil surface at slope gradient of 0.05 with mean flow discharge of 20.8 $cm^3/(cm^2\ s)$. Mean, minimum, and maximum velocity values were 34, 21, and 63 cm/s under rock fragment coverage ranging from 0% to 75% of soil surface. Guo et al. (2010) used dye-tracing method to estimate average flow velocities in their laboratory-simulated rainfall experiments on soil erosion over rock covered slopes. Results showed that flow velocity decreased from 0.24 m/s to 0.16 m/s with stone cover percentages of 5.1% and 20.8%. Under simulated rainfall conditions, laboratory experiments by Han et al. (2016) evaluated the effects of rock fragment coverage on average flow velocity of purple soil at slope of 15°. Their research did not define the relationship between flow velocity and fragments. However, the general trend showed that flow velocity decreased with increasing rock fragment content. All these previous experiments were conducted on gentle, selected or limited slopes of interests. These studies primarily aimed to illustrate the relationship between runoff depth and soil loss. However, no research was conducted to systematically collect the conjunctional effects of flow rate, slope gradient, and stone content on flow velocity.

Flow velocity is a dominating parameter in studies of hillslope hydrological processes and is closely related to erosion and transportation of eroded sediments (Chen et al., 2008; Lei et al., 2010). Runoff velocity determines the kinetic energy of water flow, which affects soil erosion and sediment transportation. Accurate estimation of runoff velocity on different contents of stone or rock fragments can benefit calculation of runoff kinetic energy; it can further provide precise predictions of the effect of stone or rock fragments on soil erosion (Nadal-Romero et al., 2013; Rahma et al., 2013; Shi et al., 2014). Mean flow velocity of shallow overland flow plays a significant role in soil erosion modeling because of its direct relationship to soil detachment and sediment transport capacity of water flow. In related models, runoff velocity can be used to deduce other hydraulic parameters, such as Reynolds Number and Manning's coefficient to determine flow status and behavior. Hence, flow velocity is a useful parameter for better understanding the effects of stone or rock fragments on soil erosion. Flow discharge, slope gradient, and soil surface conditions, as affected by stone content are directly related to water flow velocity (Lei et al., 2010; Zhang et al., 2003). Flow velocity over different stone contents soils results in different types of soil erosion.

This study used the electrolyte tracer method under pulse boundary condition following the method of Lei et al. (2005) to: 1) measure water flow velocity over stony slopes, 2) compare flow velocity over different stone contents soils under different hydraulic conditions determined by slope gradient and flow rate, and 3) analyze the effects of stone content, slope gradient, and flow rate on water flow velocity.

2. Methodology

2.1. Solute transport model

Convection and dispersion mechanisms influence salt solution transportation in water flow. Salt solution transportation is affected by factors, such as flow rate, flow velocity, and water quality. Concentrated rill water flow can be assumed to be steady and approximated as a one-dimensional flow along the stream line.

Solute transport in water flow can be calculated as a time-dependent function using the equation given by Lei et al. (2005):

$$C(x,t) = C_0 \frac{x}{2t\sqrt{\pi D_H t}} \exp\left(-\frac{(x-ut)^2}{4D_H t}\right). \tag{1}$$

where C corresponds to electrolyte concentration ($kg{\cdot}m^{-3}$), which is a function of distance x and time t and proportional to electrical conductivity of the solution, x represents the coordinate along the slope (m), u stands for the flow velocity ($m{\cdot}s^{-1}$), t is time (s), and D_H corresponds to the hydrodynamic dispersion coefficient ($m^2{\cdot}s^{-1}$).

Data on solute transport process were obtained experimentally and were fitted with Eq. (1) based on the least square method (Lei et al., 2005) to determine flow velocity (u).

2.2. Experimental materials and methods

Loess soil materials classified as a Calcic Cambisol (USDA NRCS, 1999) were collected from Ansai County on the Loess Plateau, 37°32′ N and 108°24′ E, in the hilly-gully region of the Loess Plateau in Shaanxi Province, Northwest China. The soil was air-dried and passed through a 2- mm sieve prior to measurement of compositional fractions; it comprised 23.80% of sand, 64.57% of silt, and 11.63% of clay particles. The stones used in experiments were crushed and irregularly shaped gravels with diameters ranging from 1 cm to 3 cm. The gravels were mixed with soil materials to acquire different stone contents. Fig. 1 shows the crushed stones used in this study. The stones were featured prismatic angles and rough surfaces and were commonly distributed in plateau areas.

Each soil flume was made of steel, which was 2 or 3 m long, 10 cm wide, and 12 cm deep. The prepared soil materials were uniformly mixed with stones and were used to fill the flume at a depth of 10 cm before saturation. Stony soil materials in flumes were then saturated and allowed to equilibrate for a day (24 h) before each experimental run to obtain an even initial water content distribution and eliminate any uneven soil distribution effects. Soil flumes were connected end-to-end to form 8- m long flumes on a platform to run the experiments under different combinations of flow rates, slope gradients and stone contents. The platform can be raised to desired slopes between 0° and 35°. The experimental system consisted of the following components: a water pump to

Fig. 1. The crushed stone gravel used in experiment.