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Experimental study on the spatial variation of hydrodynamic parameters for hillslope-gully side erosion system in loess landscapes

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Abstract On the Chinese Loess Plateau many hydraulic parameters related to soil erosion are highly variable and often cross-correlated. Hillslope-gully side erosion systems are widespread on the Loess Plateau, but the quantification between the hydraulic parameters is still unknown for the system. A constant headwater scouring experiment in the laboratory was performed in this study and combined a model with two slope segments (with hillslope and gully sides). Five inflow rates of 6, 8, 10, 12 and 14 L/min were used. Some hydraulic parameters (the flow velocity, shear stress, unit stream power, Reynolds Number, Froude Number, Darcy-Weisbach friction factor, and Manning coefficient) were analysed. Regression equations were developed for the parameters. The results provide a basis for in-depth research regarding the erosion processes of hillslope-gully side erosion systems.
Key words hillslope-gully side erosion system; hydrodynamic parameters; flow dynamics; flow pattern; flow friction

INTRODUCTION

Soil erosion is one of the most severe eco-environmental problems worldwide (Pan and Shangguan, 2006). Soil erosion deteriorates soil (Marques *et al.*, 2008), decreases land productivity (Lantican *et al.*, 2003) and degrades streams, lakes and estuaries as sediments and pollutants are transported to them. Due to its thick but loose and fine soil, loess hilly areas around the world, but especially in China, have suffered from severe soil and water loss (Fu *et al.*, 2011). Thus, loess hilly areas are very fragile and the main source of sediments to the Yellow River. Along with the national strategy for developing Western China, environmental issues, such as soil loss and non-point source pollution, have recently attracted greater attention in the Chinese Loess Plateau (Li *et al.*, 2009). Research regarding the erosion sediment yield law is critical for understanding sediment yield mechanisms in river basins. The sediment yield law controls the source of watershed sediments and restores the ecological environment in areas with soil and water loss. It is also important to establish a soil erosion forecast model evaluating the watershed soil and water loss environment and predicting its development. As a basic unit in the Loess Plateau, the scale of the hillslope-gully side erosion system is between the slope and the watershed. Thus the system is critical to evaluate and control soil loss on the Loess Plateau. However, research related to the system remains limited. Some research only focused on hillslopes (Nearing *et al.*, 1997). Recently, more and more researchers have realized that hillslopes and gully sides are inseparable and that dealing with just hillslopes or with gully sides cannot reflect soil erosion accurately for an erosion system (Li *et al.*, 2009). Much literature has selected parameters to reflect the hydrodynamic processes of sediment yield, such as flow depth (Merz, 1990), total discharge, discharge per unit width (Meyer *et al.*, 1975), flow shear stress, effective flow shear stress (Nearing *et al.*, 1997), runoff kinetic energy (Bagnold, 1977), effective runoff kinetic energy (Govers, 1992), unit stream power (Moore and Burch, 1986), the Reynolds number and the Froude number (*Fr*) (De Ploey, 1983). But the knowledge about what characteristics these parameters have and how they influence the soil erosion process is still limited, which results in some problems in the Loess Plateau (Gong *et al.*, 2011). This study aims to reveal the characteristics of the seven main hydraulic parameters and analyse the relationships between them with a laboratory simulation experiment. The main novelty and contribution of this study lies in the systematic and original integration of the hillslope with the gully side as a whole soil erosion system to determine the characteristics of hydraulic parameters controlling soil erosion processes in

a lab experiment with a simulation model design. The results provide insights to further uncover the real sediment yield law in the Loess Plateau, China.

EXPERIMENTAL DESIGN AND METHODS

Model design of the hillslope-gully side erosion system

In the Chinese Loess Hilly Area, the entire sloping surface is divided into either the hillslope or gully side (Li *et al*., 2009). According to the real situation in the Loess Plateau, the hillslope gradient is 10°~35° and the gully slope is approximately 40°~60° for wasteland and 25°~35° for arable land. The experimental soil box for the hillslope-gully side erosion system was designed based on this information, the principle lab design, and the Chinese Policy of Reforestation (i.e. that farm land with slope greater than 25° must be changed to forest or grass lands). The hillslopes and gully side erosion system is set as the sketch shown in Fig. 1.
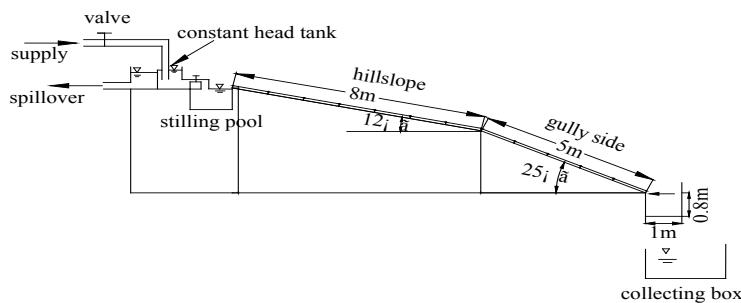

Fig. 1 The experimental soil bed of the hillslope-gully side erosion system

Experimental set-up

The constant-head water scouring experiments were conducted in the Rainfall Flood Erosion Hall of the Northwest Water Resources and Environment Ecology Key Lab of the Chinese Ministry of Education (MOE) at Xi'an University of Technology, Shaanxi Province, China. The experimental soil box was divided into two experimental portions by PVC boards. Each portion was 13 m long, 0.5 m wide and 0.5 m deep. The top section was 1 m long and was used as a transition zone. The remaining 12-m long sections were used as test zones (Fig. 1). A loessial loam soil was collected for this experiment from unfarmed land in a suburb of Xi'an. The particle size distribution of this soil is presented in Table 1. The final packed bulk density of the soil in the soil box was 1.25 g/cm^3. The soil moisture content was 10% (gravimetric), and the box was watertight and equipped with a drainage system. Before the experiment, a layer of fibre was placed in the soil box. Then a natural sand bed of 20 cm was placed on the fibre layer. The soil bed was wetted by spraying with water until the soil was saturated and no runoff water appeared. This process resulted in uniform initial soil water conditions with evenly distributed stress. The soil box was repacked for each experiment. The experiment involved five scouring inflow rates (6, 8, 10, 12 and 14 L/min), and the duration of each treatment was approximately 30 min. Clear water was introduced to the upper end of the soil bed from the stabilization pond (stilling pool) during saturated conditions. The water temperature in the pond was measured and the flow velocities were measured at each metre with the dye method (using potassium permanganate as a dye) across the entire hillslope-gully side erosion system (Guo, 2013). Flow surface width was measured across the entire hillslope-gully side erosion system at every metre with a steel ruler. Runoff and sediment samples were collected every 1 min with a 10 L plastic bucket. Each experimental treatment was replicated.

Table 1 Particle size classes of the experimental soil.

Particle size (mm)	<0.005	0.005−0.01	0.01−0.025	0.025−0.05	0.05−0.10	0.10−0.25	0.25−0.5	0.5−1.0
Percentage (%)	2.80	5.86	17.07	20.63	12.51	19.42	13.73	7.11

RESULTS AND DISCUSSION

The hydrodynamic parameters investigated in this study include the mean flow velocity (V), shear stress (τ), unit stream power (USP), Reynolds number (Re), Froude number (Fr), Darcy-Weisbach friction factor (f), and Manning coefficient (n). They can be calculated as follows:

$$\tau = \gamma RJ \quad UPS = VJ \quad Re = VR/\nu \quad Fr = V/(gd)^{0.5} \quad f = 8RJg/V^2 \quad n = R^{2/3}J^{1/2}/V \qquad (1)$$

where V is the flow velocity in m s^{-1}; R is the hydraulic radius in m; J is the hydraulic gradient; ν is the water kinematic viscosity coefficient in m^2 s^{-1}, $\nu = 0.01775/(1+0.0337T+0.000221T^2)$ (where T is the water temperature at the stilling pound in °C); d is the flow depth in m, and g is the gravitational acceleration in m s^{-2}.

According to equation (1), the mean flow velocity V is a basic hydraulic parameter, as Abrahams *et al.* (1986) pointed out. There are two standard procedures used to determine the mean flow velocity: (1) dividing the discharge by the cross-sectional area of the flow, and (2) timing the passage of a tracer (e.g. liquid dye) (Abrahams *et al.*, 1986). The second procedure was employed in this study, that is, the average flow velocity was measured during each run using the dye-tracing technique with potassium permanganate. Other hydraulic parameters (Re, Fr, τ, USP, n, and f) were then determined with equation (1).

Dynamic flow variations

Such variations can be described with mean flow velocity (V), flow shear stress (τ) and flow unit stream power (USP). The results are shown in Fig. 2. According to Fig. 2, we obtained their coefficients of variation (CVs) for the different flow discharges of Q = 6, 8, 10, 12, and 14 L/min to determine which variable is better to reflect the behaviour of dynamic flow variation. The CVs of V are 0.095, 0.106, 0.172, 0.168, and 0.227 for Q = 6, 8, 10, 12, and 14 L/min, respectively. While the corresponding CVs are 0.236, 0.344, 0.282, 0.451, and 0.416 for τ and 0.477, 0.507, 0.452, 0.464, and 0.436 for USP, respectively. The USP has the biggest CV values indicating that the USP is more sensitive to the dynamic flow variations.

The V is one of the most important hydraulic parameters for modelling soil erosion because it depends on the flow discharge, slope gradient, topography and surface condition (Zhang *et al.*, 2002; Rahma *et al.*, 2013). Furthermore, the gravitational force in the slope direction increases with slope gradient increase, which accelerates the flow velocity (and *vice versa*) (Gong, *et al.*, 2011). The τ represents the energy dissipation of the flow toward the boundaries (Nearing *et al.*, 1997). It is an important driver for removing soil particles by flow. The soil particles become detached and are transported down by runoff when the shear stress exceeds the cohesive properties of the soil particles. Flow detachment during erosion processes is often described using energy-based approaches (Lyle and Smerdon, 1965). Stream power or the USP is the energy of the flow that dissipates at the flow boundary (Nearing *et al.*, 1997). It is a better predictor of soil detachment than the τ (Hairsine and Rose, 1992), which is consistent with the changing law of CVs from the USP. Some researchers have employed the USP instead of τ to describe sheet erosion and rill erosion on hillslopes (Moore and Burch, 1986). These studies agree with the results obtained in this study.
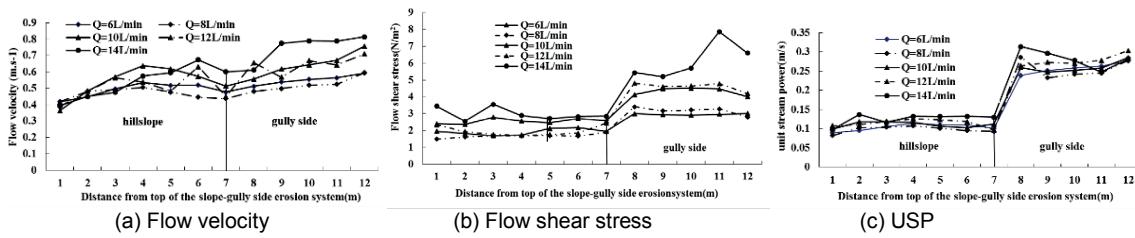

| (a) Flow velocity | (b) Flow shear stress | (c) USP |

Fig. 2 Longitudinal variations of flow velocity, flow shear stress and flow unit stream power (USP).

Flow pattern variations

It is important to characterize flow types in any erosion experiment that involves rills (Polyakov and Nearing, 2003). The Reynolds number (*Re*) and the Froude number (*Fr*) are two critical hydraulic parameters for flow regimes.

Re can be employed to determine whether the water flow is turbulent or laminar in terms of its specified critical value. In general, open channel flows are classified as turbulent when $Re > 1000$, laminar when $Re < 500$, and transitional when $500 \leq Re \leq 1000$. In this study, the *Re* values varied from 342.3 to 551.81, 404.5 to 639.77, 452.5 to 769.6, 541.26 to 828.23, or 609.46 to 858.8 when $Q = 6, 8, 10, 12$, or 14 L/min, respectively (see Fig. 3). Therefore, the runoff flow was laminar and transitional in the system during the entire experimental process.

On the other hand, the *Fr* is an important index for the state of water flow. It can be used to determine subcritical or supercritical flow and reflects the difference between the kinetic and potential energies of the flows. The runoff is considered as supercritical flow when $Fr > 1$, subcritical when $Fr < 1$, and critical when $Fr = 1$. In this study, the *Fr* values varied from 4.36 to 7.37, 2.99 to 6.95, 2.15 to 8.92, 2.60 to 7.78, or 1.36 to 8.87 when $Q = 6, 8, 10, 12$ or 14 L/min, respectively (see Fig. 3). It means that the runoff during the test process was supercritical flow.

The frictional energy losses from the flows with bigger values of *Re* or *Fr* are greater than those with smaller *Re* or *Fr* values. What is more, the frictional energy loss is closely related to the soil erosion, which has been confirmed in this study and other studies (Emmett, 1970; Abrahams and Parsons, 1994). Therefore, soil erosion in the slope-gully side system can be determined by observing the flow types of the system.
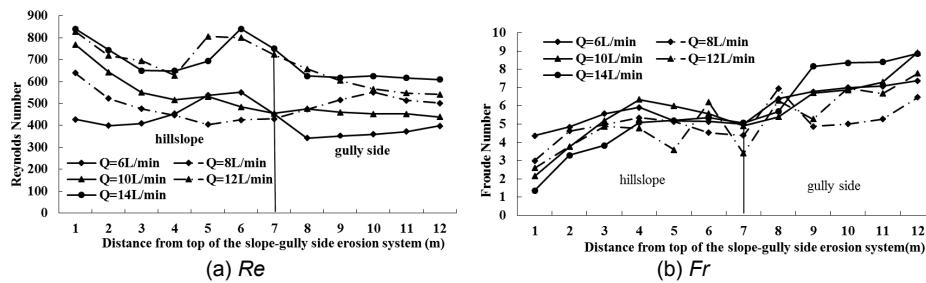

Fig. 3 Longitudinal variations of the Reynolds number (*Re*) and the Froude number (*Fr*).

Flow friction changes

Two types of resistance, flow resistance and the resistance to erosion, play important roles in the soil erosion process. Resistance to erosion is important to sediment transport, which is usually quantified by cohesion or aggregate stability. Resistance to flow can be quantified with the Darcy-Weisbach and Manning equations.

The Darcy-Weisbach friction factor (*f*) is often used as a parameter that represents the hydraulic resistance in overland flow studies that are conducted in the laboratory or field; while the Manning roughness coefficient (*n*) is widely used as a parameter for channel flow in engineering and construction. However, both methods are based on the same main variables, including flow velocity and the water depth (Guo *et al*., 2013). Takken and Govers (2000) noted that the *n* most likely behaves in the same way that the *f* does, which is consistent with the results in this study (Fig. 4). Hessel *et al.* (2003) observed similar results from their studies on erosion from steep loess slopes. The reason for this is that both the *f* and the *n* reflect the size of the resistance encountered by the slope flow during the flowing process, which can be validated by the relationship between them ($n = 0.0349 f^{0.4895}$, $R^2 = 0.99$, Table 2). Under equivalent hydrodynamic flow rate and slope conditions, more energy is consumed to overcome the resistance to water flow when the resistance coefficient is greater. Thus, less energy is available for water erosion and sediment transport, which results in weaker soil erosion. In contrast, greater energy results in more sever soil erosion (Zhang *et al.*, 2002).
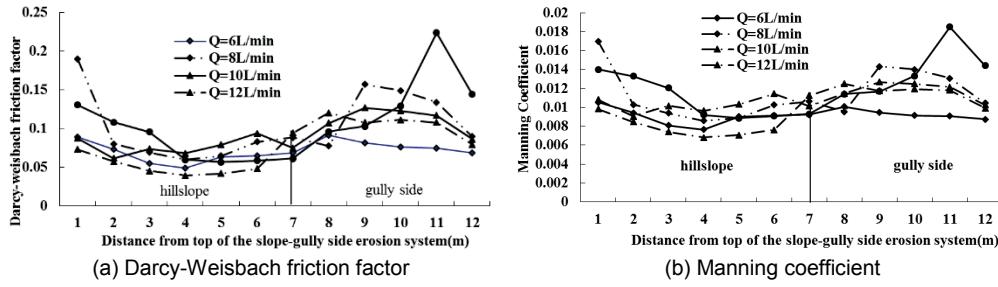
Fig. 4 Longitudinal variations of Darcy-Weisbach friction factor and Manning coefficient.

Relationships between the hydrodynamic parameters

The correlations between the hydrodynamic parameters of the hillslope-gully side erosion system were analysed. The results are shown in Table 2. These relationships in Table 2 are significant under 0.01 confidence level (2-tailed). Table 2 demonstrates that parameters of Fr, USP, V, τ, f, and n are closely related to Re by different functions, so are n to f, V to Q, τ to Fr and USP to Fr.

Table 2 Relationship with hydrodynamics parameters.

Hydrodynamics parameters set	Fitted relationship
Fr with Re	$Fr = 2 \times 10^8 Re^{-0.2752}$ $R^2=0.92$
Unit stream power(m/s) with Re	$USP = 4 \times 10^9 Re^{-3.79}$ $R^2=0.69$
Flow velocity(m/s) with Re	$V = 3607.4 Re^{-1.39}$ $R^2=0.86$
Shear stress (N/m^2) with Re	$T = -7.959\ln(Re) + 53.333$ $R^2=0.58$
Darcy-Weisbach friction factor with Re	$f = -0.293\ln(Re) + 1.9288$ $R^2=0.64$
Manning coefficient with Re	$n = -0.016\ln(Re) + 0.1134$ $R^2=0.61$
Manning coefficient with Darcy-Weisbach friction factor	$n = 0.0349 f^{0.4895}$ $R^2=0.99$
Flow velocity (m/s) with flow discharge(L/min)	$V = 0.0155Q + 0.405$ $R^2=0.8$
Shear stress (N/m^2) with Fr	$\tau = 0.5921 Fr^{-0.2044}$ $R^2=0.63$
Unit stream power (m/s) with Fr	$USP = 0.0337\exp(0.2815 Fr)$ $R^2=0.76$

Some studies (e.g. Savat, 1980; Gilley *et al.*, 1990; Nearing *et al.*, 1997) have confirmed that the *f* is closely related to the *Re* for overland flow. In this study, the relationship between them ($f = -0.293\ln(Re) + 1.9288$, $R^2 = 0.64$; see Table 2) is significant under the 0.01 confidence level. It means that *f* is also closely related to *Re*, which is consistent with the others studies (Savat, 1980; Gilley *et al.*, 1990; Nearing *et al.*, 1997). In some cases, the relationship curves between them may be different due to the different situations (such as soils, rainfalls and slopes). For example, Gilley *et al.* (1990) found that *f* was related to *Re* by a negative exponential function, which is different to the logarithmic function obtained in this study. It may imply that the relationship between the *f* and the *Re* in this study is just a special case. But to what extent the relationship between them is correct in the Chinese Loess Plateau is still unknown and needs further investigation.

At the same time, some parameters in Table 2 are confirmed to be closely related to the other ones by Savat (1980), Nearing *et al.* (1997) and Hessel *et al.* (2003). For example, Savat (1980) found that the hydraulic grain roughness decreased as the *Re* increased; Nearing *et al.* (1997) used sand and loess to study how *f* changed with slope using a constant hydraulic radius and proved that *f* decreased as *Re* increased; Hessel *et al.* (2003) had proved the *f* and *n* values can be estimated from the Reynolds number. These studies are accordant to our results shown in Table 2. In addition, some previous studies have indicated that flow velocity (*V*) is related to flow discharge (*Q*). For example, Govers (1992) showed that the flow velocity (*V*) in rills that were eroding loose, non-layered materials could be predicted from discharge data in the absence of slope or soil effects, which was also confirmed by Nearing *et al.* (1997) and Giménez and Govers (2001). In this study, we obtained a linear curve between them ($V = 0.0155Q + 0.405$ $R^2 = 0.8$; see Table 2), which is agrees with the studies of Govers (1992), Nearing *et al.* (1997), and Giménez and Govers (2001).

CONCLUSIONS

This study explored the flow spatial hydrodynamic variability of a hillslope-gully side erosion system through a series of lab-based experiments. The following conclusions can be drawn:

(1) The flow unit stream power (*USP*) has bigger coefficients of variation than the mean flow velocity (*V*) and flow shear stress (τ). The *USP* is more sensitive to the dynamic flow variations and a better predictor of soil detachment than *V* and τ.

(2) The Reynolds (*Re*) and Froude (*Fr*) numbers for the runoff indicate a significant variability between the different flows and slope positions. The runoff flow patterns were laminar-supercritical and transitional-supercritical in the system.

(3) Both the Darcy-Weisbach friction factor (*f*) and the Manning roughness coefficient (*n*) reflect the size of the resistance encountered by the slope flow during the flowing process. The *n* most likely behaves in the same way that the *f* does.

(4) The parameters of *Fr*, *USP*, *V*, τ, *f*, and *n* are closely related to *Re* by different functions, so are *n* to *f*, *V* to *Q*, τ to *Fr* and *USP* to *Fr*.

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